VISION

Visually Impaired Spatially Interactive Orientation Network

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1. EXECUTIVE SUMMARY

Every day tens of thousands of people around the world struggling with disabilities have difficulty enjoying aspects of life that many people take for granted. People that yearn to walk on, touch, smell, and see the world around them in ways that they cannot. In more recent years, technology has expanded the freedom of impaired individuals, but there is still a significant amount of work to be done. VISION enables people struggling with visual impairments to play a game of 8-ball billiards without the need for additional human interaction. The goal is to allow the visually impaired to participate in a common pastime while also feeling a sense of independence.

The idea for VISION began as an idea for making an autonomous billiards training agent that a billiards player could utilize to improve their performance. Although this was an innovative idea that can certainly help billiards players, the idea lacked a true societal impact. After much thought, the idea arose to implement a system that performed all of the tasks a visually impaired player would not be able to perform. VISION is quite literally the vision of a player that locates, localizes, and strategizes the game for a user.

VISION incorporates some of the most modern technology to implement a system that is robust yet simple enough for people without an extensive background in electronics to utilize. Upon starting the system, VISION uses a camera to capture the current state of the billiards table. Computer vision algorithms then identify all of the billiard balls on the table and determine the position and color of the balls. An artificial intelligence algorithm is then used with the billiard ball locations to determine the best shot a user can take. VISION will then track the location of the user and provide audio instructions to the user to guide the player to the correct position for the shot. Once in the correct location, the user will be guided to face in the appropriate direction to take a shot.

At this point, VISION will send information regarding the ideal shot and user positioning to a related project named SCRATCH to complete the actual shot. SCRATCH is a project working in conjunction with VISION that is responsible for the fine-tuning and execution of a user shot. Once a player has made a shot, VISION will then be able to determine the outcome of the shot and audibly notify the user of the results.

VISION is a large, complex project that incorporates many relevant topics in computer science and electrical engineering to create a product that has never been made before. VISION is an ambitious project, but the team members are committed to widening the inclusivity of one of America's favorite pastimes.

2. PROJECT DESCRIPTION

2.1 Project Background and Goals

Billiards is a collection of many different games played with a billiards table, cue stick, and several colored billiard balls. The objective of a billiards game varies depending upon what specific game is played, but the typical goal is to use a cue stick to pocket a targeted game ball. Every specific billiard game introduces rules and requirements that make sinking a shot more difficult than it may seem. One of the more common billiard games, and the focus of this project, is 8-ball pool. The goal of VISION is to design and implement a system that allows individuals suffering from visual impairments to become capable of playing a game of 8-ball billiards.

Billiards was selected as the game of choice because of its significant complexity compared to other games such as chess. Chess is a game commonly associated with masterful planning that requires crafting moves multiple turns in advance to be successful. Although chess certainly is a complex logic game, it is a discrete problem in terms of computation. Chess has a fixed number of locations on the board, a specific number of pieces with strict rules about where they can move, and a finite number of possible ways for the game to progress. All of these reasons have led chess to become a commonly studied problem in computer science. There are many computer programs and algorithms for chess that are quite good at the game. There has been much less research conducted on creating a robust billiards program. Furthermore, there does not appear to be any billiards-style game developed specifically for the visually impaired.

Like chess, billiards also requires players to plan their moves many turns in advance in an offensive or defensive manner. An offensive move is when a player tries to sink as many balls as possible while a defensive move is when a player tries to put their opponent in a position such that their opponent cannot complete a shot. The careful shot selection necessary for billiards is significantly more involved than the equivalent chess decision because there is an infinite number of positions that the state of the billiards table can be in. The billiard balls can arrange themselves in any position on the table at any point during the game, the same cannot be said for chess. There are many ways for a game of billiards to progress, and it can oftentimes be difficult to know what the best shot to take is given the current state of the game.

For the vast number of chess programs and significantly fewer billiards programs that have been developed, nearly all of these projects have been software implementations of the game. The programs that were created were designed to be used for virtual games, not physical chess boards or actual billiards tables. The versions of billiards games prove that a software system can be used to implement a game of pool. One of the goals of VISION is to expand upon previous work by using an actual game of billiards, rather than a simulation of the game.

The success of VISION will be determined if an individual dealing with visual impairments is able to successfully compete in a modified game of billiards (with the assistance of the SCRATCH team). With the help of VISION, a user should have the billiards table represented algorithmically and have the best shot determined for them. The user's location should be tracked and used to navigate the user around the billiard table to the desired position for the shot. If all of these individual goals are met, VISION will be a success. VISION should be compact and portable so that the system can be disassembled, moved, and assembled in a timely manner.

2.2 Project Motivation

The motivation of VISION is to develop a systematic way to represent a real-life game of 8-ball pool computationally and then develop an elegant way to guide a visually impaired user through the best shot for them to take to win the game. VISION is a tool that can leverage the power of modern technology to help improve the inclusiveness of one of society's most popular pastimes.

For VISION to truly have an impact, the team decided to develop it in a way that allows individuals dealing with visual impairments to develop a sense of autonomy. There are not many games that have support for people dealing with disabilities. It can be difficult for some individuals to feel included when they are not able to participate in the same pastimes as their friends and family. Globally, about 295 million people have a case of near or far distant visual impairment. In addition to this, about 43 million people worldwide suffer from complete blindness. One of the biggest troubles they face in their everyday life is having their freedom limited by moving in an obstructed or limited environment where spatial awareness is preventing them from being able to engage in their daily activities.

A lot of systems are in place in different media to help counteract or ease these issues to breach issues of orientation, localization, and way-finding through different technologies. Navigation technologies or electronic travel aids have been the backbone when it comes to developing technologies to help visually impaired people bridge the way for more specific applications such as the one developed for this project. Similar to the goal of VISION, a lot of sports rules have been adapted and modified to develop games that are more inclusive to visually impaired individuals. For instance, beep baseball where the bases beep to let the players know which direction they need to go in, or soccer where the regular ball is replaced by an audible ball. These concepts were used as motivation and a basis to determine which objectives and checkpoints are needed to make VISION an impactful visually impaired technology. Our team has broadened the inclusiveness of billiards by creating a system that leverages technology to plan, strategize, and see for a player.

2.3 Project Function

A visually impaired individual that is using the VISION system has the system locate all of the billiard balls and determine the optimal shot for them to win the game. VISION actively tracks the user and guides the user to the required location through audio instructions. The system provides instructions to the user to ensure that they are positioned in the general direction of the cue ball. At this point, VISION's job is complete and the SCRATCH program (group #17) will take over. VISION will provide SCRATCH with the optimal shot angle and required force.

There is certainly a concern when two projects are interrelated with each other in Senior Design. It would not be fair if one project's failure leads to the failure of the other project. With the help of our mentor, the teams designed their projects in a way that minimizes interaction between the two projects. VISION will transmit two quantities to SCRATCH and the two values can easily be artificially constructed if needed. The SCRATCH team does not need to transmit any information back to the VISION team. If the VISION team fails to complete their project, the SCRATCH team can craft inputs that the VISION team should have provided. If the SCRATCH team fails to complete their project, the VISION team will lay the groundwork for future work. VISION detects billiard balls, finds the optimal shot, tracks the user, guides the user to the appropriate position, and positions the user in the appropriate direction.

The VISION team has designed a system that is lightweight and able to be moved between different locations. The system is designed so that it can quickly be disassembled and reassembled so the team can work on the project in a variety of locations and environments. The mobility of the system will also be helpful when demonstrating VISION to others and must be set up in different locations.

VISION is a large project that incorporates many technologies into a single, user-friendly system. The central processor for the system is a powerful, computer-like processor capable of running computer vision and artificial intelligence algorithms. There are many systems that must be integrated for VISION to work properly. Figure 2.1 below shows a block diagram of all of the systems needed.

All systems are controlled by the powerful central processor shown in the middle of the diagram. The processor asks the computer vision system to capture the current state of the board with a camera and transforms the physical billiards game into data expressed in a computational way. The shot selection algorithm is then used to determine the best shot to take given the current state of the table. The shot information is used by the user localization and user guidance systems to determine where the user is and how to guide them to the proper location. Once the user is in position, the control will be transferred to the SCRATCH team to take the actual shot. Once the shot has been executed, VISION takes back control and determines the results of the player's shot. The results are announced through an audio system.

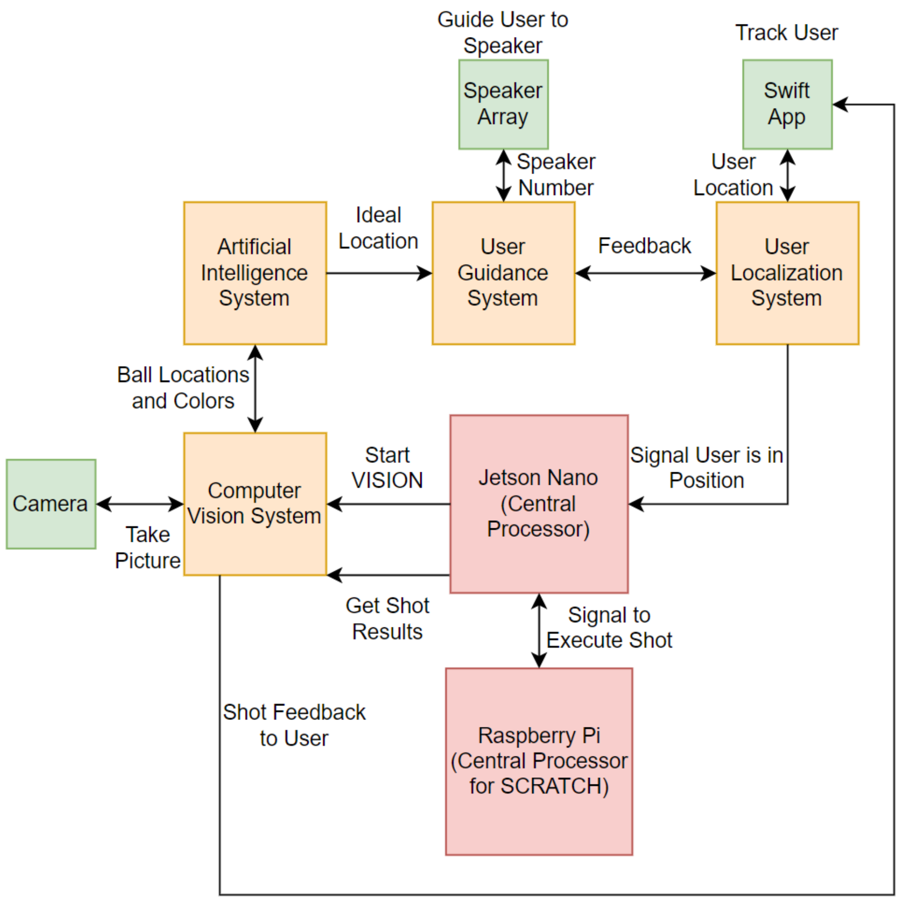


Figure 2.1 Project Block Diagram

2.4 Project Objectives

VISION encompasses a system that captures the current state of the pool table at every point during the game, that is, at the start of a game, and every round during the game. This system processes the images to isolate the pool table from any sort of background present in the image. The system detects, isolates and localizes the billiard balls present on the pool table. The system differentiates the cue ball, the eight ball, the player balls, and the opponent balls.

VISION encompasses a system that computes the optimal shot that the user, visually impaired or not, can make based on a shot selection algorithm. This involves making considerations and assumptions such as the skill level of the user, outside interference during the shot, and other relevant factors. The algorithm provides how much force would need to be put to make the shot, the positioning of the user's hand on the cue stick, the angle from the base of the table to the cue stick, user posture, and other related metrics.

VISION encompasses a system that navigates the visually impaired user to the necessary position that the aforementioned algorithm determines, the position in which he/she has the best odds to make a ball. This system relies on the previous systems to determine what the optimal location of the user is to take the desired shot. This calculation is needed after every shot the user takes. The system also navigates the visually impaired user through audio methods.

VISION encompasses a system that allows a visually impaired individual using the system to be detected around the pool table. VISION uses wireless beacons placed around the table to locate the user. An application on the user's phone is used to track the current state of the user.

VISION encompasses audio outputs to vocalize shot results and important information about the game progression. Considerations would need to be taken to avoid audio overload because audio is also being used as a way to navigate the user.

All of the components of VISION are modular and were individually tested before being integrated with the entire system. The components of VISION can be assembled and disassembled quickly. The entire system can be transported in a sedan so that there is no problem moving the system from one location to another.

VISION is a self-funded project and also would like to be made affordable enough for someone to reproduce themselves. For these reasons, the team has kept the project under $800, so each member did not have to contribute more than $200.

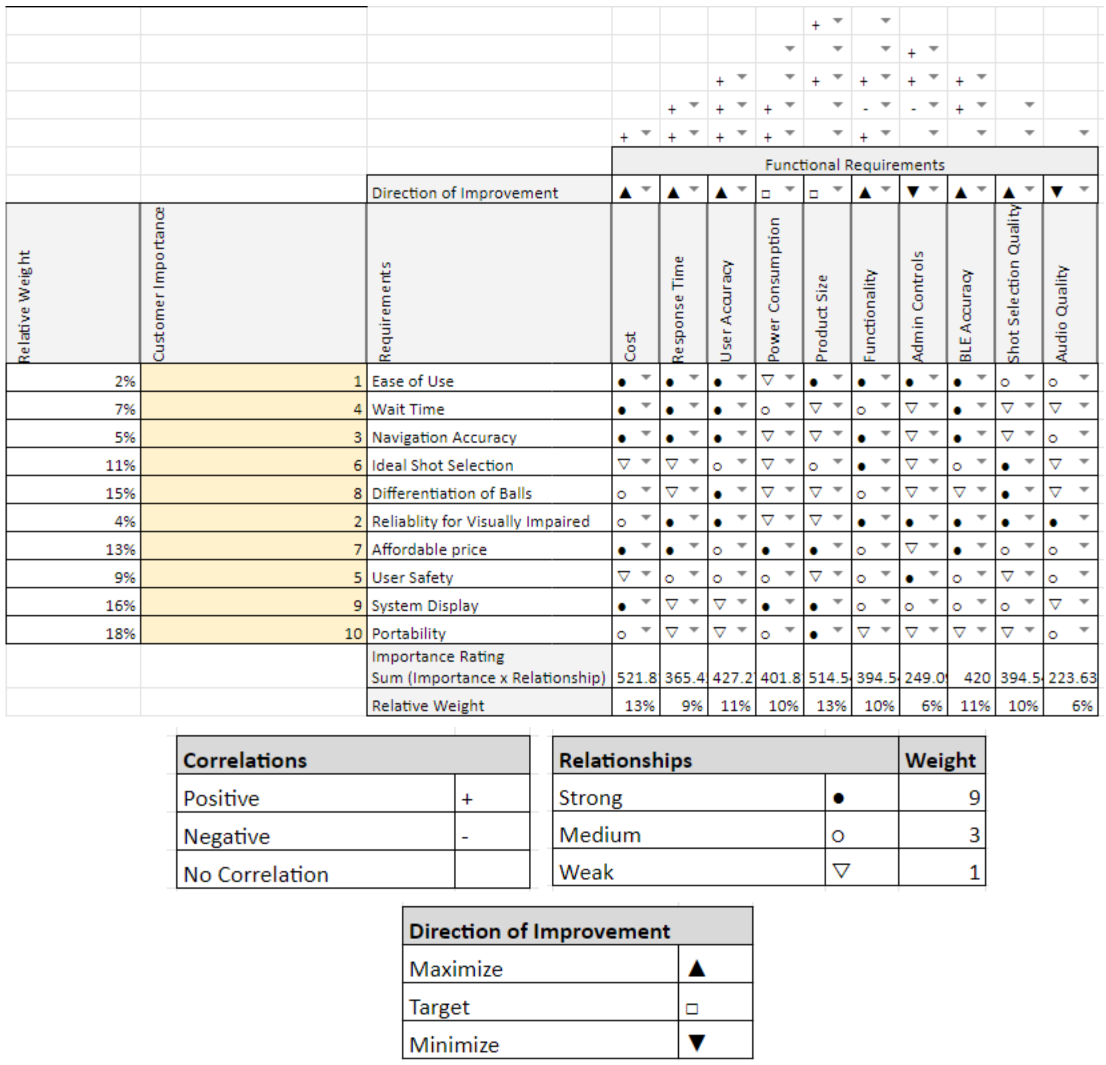
2.5 Required Specifications

The previous sections describe the goals, objectives, and motivation behind VISION. To transform VISION from an idea into an actual project, requirement specifications must be clearly defined. These requirements are what the VISION team used to bring the project to life. These requirements served as a contract between the team members and the senior design advisors clearly stating what the project will be able to do. The success of VISION is based on meeting the requirements specified in table 2.1.

Requirement	Description
1.1	Locate up to 10 billiard balls on the billiards table
1.2	Differentiate between green, blue, black, and white billiard balls with at least 95% accuracy
1.3	Locate all balls in an (x,y) coordinate system within 15 pixels
1.4	Latency of the computer vision system does not exceed 5 seconds
2.1	Latency of the shot selection algorithm does not exceed 25 seconds
2.2	Shot selection algorithm will produce a shot suggestion with a minimum specificity of 5 degree increments
2.3	Shot selection algorithm will produce a shot suggestion with a minimum specificity of 5 force levels
3.1	Latency of the user localization does not exceed 10 seconds
3.2	Accuracy of the user localization is within 1 foot of true location
3.3	Localization aid should work independently of the surroundings
4.1	Position user within 1 foot of desired standing position for shot
4.2	Orient user within 15 degrees of desired shooting direction
4.3	Latency for communicating with the central processor does not exceed 1 second
5.1	VISION can be assembled or disassembled in less than 30 minutes
5.2	The total cost of VISION should not exceed $800
5.3	The product's audio aids will support the English language
5.4	Battery-powered devices used within the system should be viable for 1 year

Table 2.1 Requirement Specifications

To best quantify the correlation of various portions of VISION's defined deliverables and scope, the house of quality shown in Figure 2.2 was devised. The table connects the required deliverables shown on the left side of the table to important functional factors of scope shown on the upper row. Those required deliverables are additionally ranked by level of importance. The interior bulk of the table relays the correlation direction between these factors, a solid dot representing strong, hollow dot representing a medium, and a down arrow representing weak correlation. A similar metric is utilized on the roof of the house with positive and negative signs measuring the correlation between the functional requirements of the scope to one another. These features are connected diagonally with one another. The direction of improvement is added at the conclusion of the additional importance ratings as this allows for the team to best approach areas that require attention due to their high relation to the success of the project. The table shows the areas with the highest relative weight to be the most crucial to project success. This includes areas of accuracy, response time, functionality, and overall cost.



							+					
									+			
					+		+	+	+	+		
				+	+	+		-	-	+		
			+	+	+	+		+				
			Functional Requirements									
		Direction of Improvement	▲	▲	▲	□	□	▲	▼	▲	▲	▼
Relative Weight	Customer Importance	Requirements	Cost	Response Time	User Accuracy	Power Consumption	Product Size	Functionality	Admin Controls	BLE Accuracy	Shot Selection Quality	Audio Quality
2%	1	Ease of Use	●	●	●	▽	●	●	●	●	○	○
7%	4	Wait Time	●	●	●	○	▽	○	▽	●	▽	▽
5%	3	Navigation Accuracy	●	●	●	▽	▽	●	▽	●	▽	○
11%	6	Ideal Shot Selection	▽	▽	○	▽	○	●	▽	○	●	▽
15%	8	Differentiation of Balls	○	▽	●	▽	▽	○	▽	▽	●	▽
4%	2	Reliablity for Visually Impaired	○	●	●	▽	▽	●	●	●	●	●
13%	7	Affordable price	●	●	○	●	●	○	▽	●	○	○
9%	5	User Safety	▽	○	○	○	▽	○	●	○	▽	○
16%	9	System Display	●	▽	▽	●	●	○	○	○	○	▽
18%	10	Portability	○	▽	▽	○	●	▽	▽	▽	▽	○
		Importance Rating Sum (Importance x Relationship)	521.8	365.4	427.2	401.8	514.5	394.5	249.0	420	394.5	223.63
		Relative Weight	13%	9%	11%	10%	13%	10%	6%	11%	10%	6%

Correlations	
Positive	+
Negative	-
No Correlation	

Relationships		Weight
Strong	●	9
Medium	○	3
Weak	▽	1

Direction of Improvement	
Maximize	▲
Target	□
Minimize	▼

Figure 2.2 House of Quality Analysis

3. RESEARCH

This section of the paper covers the major topics of interest for VISION. From past projects to relevant technologies, this examination allows for technological solutions to be devised and properly informed for the project's design stage.

3.1 Similar Projects

Billiards Assistive Device for the Physically Challenged: A user assistive physical device was developed by the University of the West Indies to assist a user that was physically impaired and lost certain motor skills due to an accident. This mechanical device was aimed to improve grip strength, leading to improvements in overall performance.

Open Pool: This open source project is built around adding visual effects to the game of pool. By using computer vision powered by OpenCV, the computer can generate graphics by using the Unity game engine. This open source project gives step by step directions to set up both the hardware and software required for the project. The project requires a gray colored pool table, a Kinect Two for Windows, a computer with Windows OS, and a projector. The main areas of interest come from the computer vision code available. The main issue is that the project has not seen much maintenance since 2014. With all of the recent innovations in computer vision, it is unlikely the open source code can be used without major refactoring. However looking into the basic setup of the software, the OpenCV code may be of great benefit in our design strategy later on. Another feature of the project is code for detecting made shots, or "pocket detection" as the project named it. While they have released software for this feature, there is currently no hardware requiring us to fabricate the physical detection system ourselves.

3.2 Relevant Technologies

VISION does not aim to create a new form of technology, but rather incorporate many existing forms of technology into an innovative, inclusive system. The members of VISION have each become subject matter experts in their respective area of focus and have summarized their findings throughout the rest of this section.

3.2.1 Billiards Artificial Intelligence

3.2.1.1 Simulation Tools

The need for rapid simulation of games is needed to test the different shot selection approaches. These simulations do not encompass every shot parameter, but will let VISION make comparisons among the decision making models. Another effective strategy is to model more realistic conditions that introduce noise to the simulations as well. By adding a normal random change to both shot power and angle VISION can better model a person.

Summary of Requirements:

- Latency of the shot selection algorithm does not exceed 25 seconds.
- Shot selection algorithm will produce a shot suggestion with a minimum specificity of 5 degree increments.
- Shot selection algorithm will produce a shot suggestion with a minimum specificity of 5 force levels.

Pool: This is the simulation software that was implemented in the paper "Deep Cue Learning: A Reinforcement Learning Agent for Playing Pool". The simulation software is further described in the reinforcement learning section below. This is an openly available project on GitHub.

Fastfiz: This is a version of the software Poolfiz and was used by the heuristic based model described below. This is an openly available project on GitHub.

Pooltool: This is a three dimensional simulation system for pool. The GUI operates very slowly, most likely because it is written in Python and has to handle 3D graphics. In order to be an effective option VISION would have to disconnect the shot selection algorithms from the graphical interface. The actual calculation of the shot however seems to take up a considerable amount of time as well. Dependency issues have been encountered while trying to use a special API for setting up physical simulations. In the documentation the author claims to not have put much work into the API thus far, and with little documentation, it may not be a very suitable choice. This is an openly available project on GitHub.

Ultimate Pool Simulator: A simulator written in Java. This simulation project has a built in GUI and multiplayer mode, allowing for each player to choose a shot. It was developed by a group of students for a class project and the physics would have to be evaluated extensively. This is an openly available project on GitHub.

Code Bullet Pool AI: This code has no documentation on its github page, the author created a YouTube video for the project, but it is little help for setting up the project. It appears the code is written in an object oriented language such as Java or C++, but the .pde file extension makes it difficult to distinguish. The very limited documentation and no test cases lead the team to believe this will be a difficult project to base VISION on. This is an openly available project on GitHub.

Pool Genius: Pool genius features a GUI for displaying the shots that significantly slows down the program's performance. One shot took over 45 seconds to process, with only one ball remaining that was cut down to 10 seconds. The simulation is very slow and the overall shot selection process would need to be revised. This is most definitely not ideal for any sort of computations and would be much too slow for VISION. While the shot selections are perfect, VISION may be able to tune down the performance on these in order to speed up computation. Another major consideration for this code is that there are no test cases currently available. Without these unit tests, it will be much harder to understand the code, as well as to make changes without breaking much of the functionality in unforeseen ways. This is an openly available project on GitHub.

PickPocket: This is a software developed by Micheal Smith, it is covered extensively in the section labeled Search Algorithms. The code is not openly available and we would have to request the source code, which is less preferable to an open source project with more documentation. The source code for this project was able to be obtained from Michael Smith.

3.2.1.2 Simulation Tool Modifications

Shot Selection Algorithm Guidelines: The shot selection algorithm is the primary way of deciding what angle and with what force to hit the cue ball. For the purpose of this research, VISION is looking at the table from an overhead 2D perspective. This leaves out many important aspects of the game of pool, such as allowing for rotational momentum of the ball to change the shot. The available simulation software makes it difficult to account for another axis. It would also be extremely difficult on any machine learning algorithms to add another axis for our output.

Limitations of Shot Selection Algorithms: The shot selection algorithm's usefulness is limited by human ability. The best shot may require perfect accuracy to hit correctly, and may be much more difficult than a safer alternative. That is why in most cases, the easiest shot is the best shot. For example, an algorithm may say there is a way for the player to make three balls at once, but it may require more precision than a human is capable of and may increase the risk of losing if a miss occurs. Another issue will be the communication from the algorithm to the person. Even if an accurate algorithm is produced, there must be a suitable way to communicate the power needed on the shot. Another issue is placing the user in the right location to hit the cue ball. Finally, the user may also strike the ball in an unpredicted way upon the vertical axis which the algorithm does not take into account. All of these factors lead to issues which must be taken into account for VISION's algorithm.

Planned Simplifications: In order to simplify the model, VISION will be focusing on a game in which only the horizontal angle of the ball will be struck. This takes away the need to calculate spin on the ball, bringing down the complexity of shot selection immensely. VISION will also need to come up with a shot selection algorithm for the solid colored balls.

3.2.1.3 Different Implementations of Shot Selection Algorithms

Heuristic Model: This model is based on a research paper labeled "A Heuristic-Based Planner and Improved Controller for a Two-Layered Approach for the Game of Billiards" written by Jean-François Landry, Jean-Pierre Dussault, and Philippe Mahey (Landry et al.). This model used the Fastfiz simulator for simulating shots during testing. This model takes in five parameters : α horizontal offset from the ball's center, b vertical offset from the ball's center, θ angle of the cue stick in relation to the plan of the table, ϕ orientation of the cue stick, and v initial speed given to the cue ball. The simulation tool Fastfiz is deterministic, so noise is added to the shot parameters to make results more realistic. An interesting heuristic found by the paper deals with safety shots, these are shots which are made to make it more difficult for the opponent to make a shot. These were determined to be impractical unless all other possible shot selections have a low probability of success. This is due to the difficulty of guessing what shot your opponent will take. The model in this paper uses a two layer approach, the name given to these two layers are the planner and the controller. Figure 3.1 below gives an overview of the planner architecture.

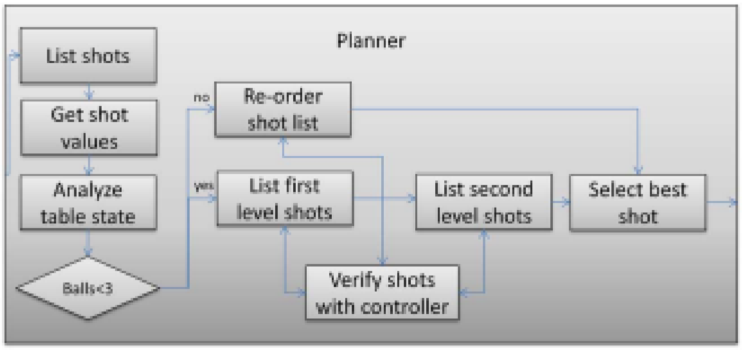


Figure 3.1 Shot Planner Diagram

The high level planner uses several domain specific heuristics in order to narrow down the search space for the shot selection algorithm. At the beginning of a turn the planner determines which shots are possible, with this it creates a shot list made up of direct, combination, and indirect shots. It also lists all the pocket ball combinations. After this, the algorithm goes over the shot list and creates a difficulty value for every single shot on the list.

Another heuristic used by their algorithm is to always prefer shorter shots. The most successful approaches are the ones which require the cue ball to travel the least distance. This is due to the longer distance traveled creating for greater deviation from desired outcome as well as increased speed leading to more powerful and chaotic collisions. Another approach which was used was through the implementation of a k-means clustering algorithm which grouped the balls into different clusters. The reason that this method was added was to hit closest shots first, as those were generally the strongest shot choices. Another function found in this research is their formula for creating a function to penalize possible shots based on difficulty of the shot. For an easy shot, the direction is almost insignificant as long as the ball is tapped on a certain side. For more difficult shots, there is a much smaller area which the ball must be hit at and with a certain speed. An easy shot also allows for better positioning options, if there is a wider range of area on the ball you may hit to sink it into a hole, you then have more places to position the cue ball after the hit.

<u>*Reinforcement Learning Model:*</u> The reinforcement learning model is based upon trial and error in game-like situations. It is a machine learning algorithm implemented by using rewards and punishments. This model will find a locally optimal way to achieve a victory, or at least to maximize points. It is one of the most widely used models for creating an artificial intelligence system for games and therefore will serve well for pool. This will be much less time intensive than a supervised learning model. In a supervised learning model, the algorithm would imitate a human player. This would also create a model only as good as one of the VISION team members, which is not at all optimal.

Assigning what constitutes a reward and punishment, as well as the relative weight of each is perhaps the most difficult part of designing a reinforcement learning system. VISION will try many different assignments, but some of the different rewards and punishments would be the following:

> Rewards: made ball (+1) or win game (+10)
> Punishments: made opponent ball (-1), scratch (-1), lose game by opponent(-5), or scratch on 8 ball (-10)

These systems often come up with unique methods that are not very intuitive. These shot selections may go against common knowledge and may be a poor way to teach newer pool players. Therefore VISION must thoroughly analyze this model once it is created to ensure that the shots selected are logical. On the other hand, this system may come up with better ways to cope with noise introduced to the system. A heuristic based model will work the same regardless of noise, but the reinforcement learning can learn to play with different levels of noise, thus modeling different skill levels of players. Exact thresholds for noise levels to model different levels of players would be arbitrary, but can be found by trial and error on our selection for the pool simulator. The source code for this project can be found on a publicly available GitHub repository as well.

VISION will be basing its research on a pool specific reinforcement learning model using a Markov Decision Making process with four different reinforcement learning algorithms: Q-Tablebased Q-Learning (Q-Table), Deep Q-Networks (DQN), and Asynchronous Advantage Actor-Critic (A3C) with continuous or discrete values (Liao et al.). This process is trained on the open source simulation project labeled “pool” in section 3.2.1.1.

Markov decision making process (MDP) is for modeling discrete decision or optimization problems where there is randomness and uncertainty in the problem. It can be represented mathematically as a 4-tuple (S, A, P, R) where:

> S is the set of states, called state space
> A is the set of actions, called the action space
> P is probability that action a in state s at time t will lead to state s’ at time t + 1
> R is the reward for transitioning from state s to s’ after action a

The sum total of different states may be finite or infinite, depending on the application. A game such as chess would have a finite number of different states to choose from, as well as discrete choices, making it a much easier decision making process. Pool on the other hand has a continuous range of actions as well as an infinite amount of possible states. The solution to an MDP is called a policy. This policy is a mapping from the current state to the preferred action in order to maximize rewards. This policy will form what is known as a markov chain, as the new state will also have a mapping to the next best state to achieve the best overall reward. A note about the markov chain is that it maps more than one probability, though the highest probability for reward will be selected in our case, there will be other paths that also offer reward from any state action pair. For the game of pool this will be very difficult to model. One such solution would be to choose the nodes of the MDP chain to be ball pocket pairs. This will however make it rather difficult to model shots that either hit the side of the pool table, or another ball before falling into the pocket. This method would also introduce much ambiguity in terms of angle and power, as there is a wide range of angles to result in any given ball pocket combination. Another option would be to discretize the power and angle of all shots. A discrete and finite pool action set would be as follows:

A = (Force, angle) = (F, $\boldsymbol{\theta}$)
F = [1, ... ,10]
$\boldsymbol{\theta}$ = [1, .. , 360]

A discrete and finite pool state set would be as follows:

S = [x_1, y_1, …, x_n, y_n]
Pool table is 127cm by 254cm, diameter of ball is 5.715cm, radius = 2.8575
Assuming y = [0, 253]
Assuming x = [0, 126]
Some values will be labeled as impossible to reach due to size of pool ball
* n is total number of remaining balls
* x_1, y_1 is the cue ball

Q-Learning: This is an algorithm to make the best selection in a MDP, otherwise known as a policy. This model learns the Q-values for every action and state pair. These Q-values are stored in a Q-table that maps actions on the horizontal axis and states on the vertical axis. The Q-learning method is applicable to a finite MDP. As mentioned previously simplifying the actions in the game of pool to a finite MDP can be difficult, the approach taken by the writers of the previously mentioned paper was to simplify the game of pool, similar to how was done above. The Q-learning algorithm works by referring to the Q-table and picking the action with the highest Q value for the given state, during training when the Q-table is empty the agent will make random actions in order to learn the different rewards for taking those actions, eventually filling in the Q-table. The main reason for this algorithm is to better understand delayed rewards in the system. There is a variable γ which represents the discount factor, when set to zero, the algorithm is myopic and simply picks the best current rewards (greedy algorithm), but by increasing this value, you find a path which gives higher long term rewards. An example Q-learning model is shown below:

$Q^{new}(s_t, a_t) = Q(s_t, a_t) + \alpha(r_t + \gamma\ (\max Q(s_t, a)) - Q(s_t, a_t)\ )$
α is the learning rate
$Q(s_t, a_t)$ is the old value
$\max Q(s_t, a))$ is the best estimate of the optimal future value
γ is the discount factor

<u>*Deep Q Networks:*</u> This is used due to the fact that Q-Learning works well for a small number of state action pairs, but as this number grows, the algorithm becomes less efficient. In the case of a modeling pool, the number of table states is already so large, when paired with the vast amount of actions and the size of the Q-table grows too rapidly for most computers to handle. In the paper above, the Q-table for a simple two ball system was approximately 1.12 GB, and this number grows drastically as other balls are added onto the table. In order to combat this explosive growth of the Q-table size VISION will use a new learning algorithm. The total size of the state and actions pairs for the simple model would be on the order of (Action set * State set $)^n$ where n is the number of balls.

A deep Q network employs a neural network in order to come up with an approximation for the Q-learning algorithm. The input nodes for the neural network are the current state of the table and the output nodes on the deep Q network represent every possible action. The value for that output node is the approximated Q-value. In VISION's simplified case, 3600 output nodes is still significant, but the action set is much smaller than the state set and this is a preferred method in terms of space complexity. The total size of the model achieved in the paper was approximately 162 KB. The neural network consists of two hidden layers of 64 and 256 nodes respectively. Figures 3.2 and 3.3 below are two representations of what such a model may look like.

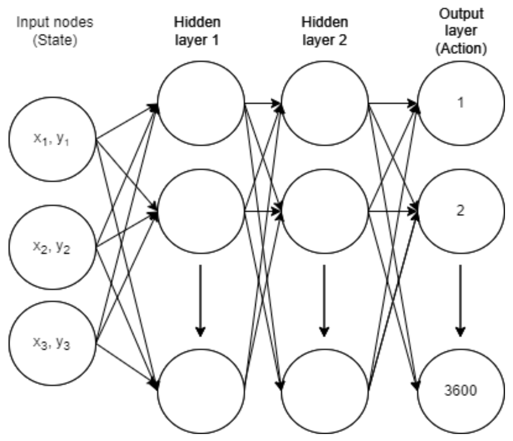


Figure 3.2 Neural Network Work for State Set with Three Balls

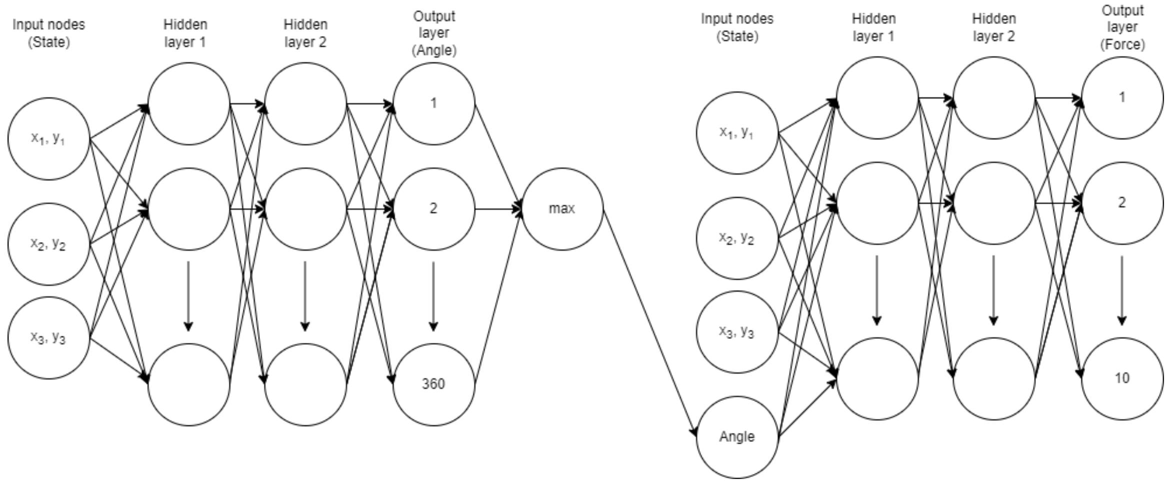


Figure 3.3 Neural Network for State Set with 3 Balls (Broken Into Two Networks)

<u>*Asynchronous Advantage Actor-Critic (A3C):*</u> This algorithm was developed by Google Deep Mind and first appeared in 2016. A3C implements several workers to gather information independently and asynchronously, then by using this information in a global network, the function value and policy may be estimated. While Deep Q-networks only use one environment and one agent in their training, AC3 uses several environments and agents. These agents act completely isolated from one another in their learning process, this allows for more diversified training and avoids local maximum optimizations. The other benefit of A3C is that it is useful for a problem with infinite space and infinite actions, meaning that it offers the most precise actions for any given space. This is done by breaking the model into an actor and a critic. The actor model takes in the environment and chooses the best possible action with its current data, while the critic model takes in the environment and acts as an evaluator for that choice.

The overall consensus put forth by the paper is that the A3C model was the most ideal model taking into account the training time and required space. The results for the models compared to the random baseline are not particularly impressive and would require refactoring to even get a usable amount of precision. Ultimately these algorithms do not seem to compare to the precision of search and heuristic based models. The benefits of dealing with noise in the system may be a reason to attempt to build a custom model for VISION.

<u>*Search Based Model:*</u> The research gathered for this section is for search algorithms in the game of pool. One major search based shot selection algorithm is known as "PickPocket" (Smith), this program would go on to win the first international computer billiards competition. One of the key points made is the inherent difficulty of using a search algorithm on a non deterministic and continuous set of outcomes. Search algorithms are a perfect way to choose the best move in a deterministic and discrete game such as chess; however, the difficulty is magnified in the game of pool. Another disadvantage is the considerable overhead required by the search algorithm to run a physics engine to determine the outcome of a given shot. This physics engine severely

limits the breadth of the search tree. One such search algorithm suggested by the author is the Expectimax search algorithm.

The Expectimax search algorithm is a game theory algorithm that is a variation of the Minimax algorithm. While the Minimax algorithm expects the adversary to act optimally, the Expectimax algorithm expects the adversary to make non optimal decisions based somewhat on chance. The tree structure for this algorithm depends on nodes labeled as change nodes. These nodes in the search tree represent points where the outcome is non-deterministic. An abstraction must be made in order to simplify the problem and use Expectimax. A pocketed shot effecting no other balls will result in a particular table state, while the missed shot can result in an infinite amount of different table states.

Another model which is brought up by the author is the Monte-Carlo simulation. This model is used in everything from modeling the card game poker to financial risk. The main purpose is to calculate probabilities of outcome when random intervention of variables is present. For the Monte-Carlo simulation, a number of samples or table states is calculated after each generated shot, each sample is a child node of the previous shot. This pattern trickles down to form a tree-like structure, with the score of each node being the average score of all the nodes children. The higher the number of samples, the more accurate the results. However the runtime increases exponentially as the number of samples are increased, therefore a proper balance must be found when using this simulation. When comparing this Monte-Carlo simulation to the previously mentioned Expectimax, you will see the main trade off is breadth vs. depth. The Monte-Carlo simulation has a much wider tree structure while the Expectimax is able to create a deeper tree structure.

3.2.1.4 Computation of Shot Selection Algorithm

The shot selection algorithm requires a system with high computational power for either a large search algorithm or heuristic algorithm. For a mathematically intensive machine learning algorithm, VISION would require a large computational resource for the training phase, but would require significantly less compute power thereafter. The use of a microcontroller will not be able to handle the large amount of processing needed. The options for VISION’s main processor are a microprocessor or a cloud computing solution.

Cloud Computing: In order to compute the function on a powerful machine and in a cost effective manner, one strong candidate is an Amazon Web Service product called a Lambda function. The lambda function allows you to run code on the cloud without having to manage the infrastructure. Instead of configuring and running a server on the cloud which is paid for based on time, you can instead use a lambda function which is paid for by usage. It has a strong use case for IoT backends and can be scaled quickly based on requirements. Amazon Lambda is currently on the free tier of AWS services and would be free to use for our small number of requests. There is also native support for Python, Java, Node.js, PowerShell and C# among others. This wide variety of options will allow VISION to implement almost any shot selection algorithm in the cloud. There is also a low amount of data being input into the lambda function as well as returned by the Lambda function. This means that wireless communication bandwidth will not cause any large issues.

3.2.2 Computer Vision

3.2.2.1 Computer Vision Software Options

The computer vision portion of this project is the initial input to the entire system. An image will be captured from the camera and then processed by the selected computer vision algorithms. The chosen algorithms should be able to identify all of the billiard balls on the table, determine the position of all of the billiard balls on the table, and determine the colors of the billiard balls. The cue ball and eight ball, due to their importance in various billiard games, should also be distinguished from the other billiard balls on the table. The output of this subsystem are the coordinates and colors of all the billiards balls in play.

The billiard balls can be identified by searching for circular contours, or outlines, of a specific size in the image. The position of the billiard balls can be determined by utilizing the location of the circular contours previously found. All of the incorrectly-detected objects can be excluded by checking the size, shape, and color of all detected objects to ensure that only billiard balls are tracked. Finally, the ball color can be determined by checking the RBG values of the discovered contours.

The requirements for this project are relatively common in computer vision and many of the current computer vision offerings are more than capable of the required functionality. The ideal software package for this project will require the least amount of computing power while ensuring high accuracy for detecting and locating the billiard balls. Furthermore, the ideal software will have a low latency to allow a user to play a game of billiards in a reasonable time. The requirements for the system are summarized below.

Summary of Requirements:

- System can locate up to 10 billiard balls
- System can differentiate between white, black, green, and blue billiard balls
- System can locate the balls in an (x,y) coordinate system with 15 pixels
- System latency does not exceed 5 seconds

OpenCV: OpenCV is a computer vision and machine learning library that provides C++, Python, Java, and MATLAB interfaces and is supported by all of the major operating systems. The library is open source and contains thousands of ready-to-use computer vision algorithms that have been used by many prominent companies like Google, Microsoft, Intel, IBM, Honda, and Toyota (OpenCV "About OpenCV"). OpenCV offers extensive support by providing forums, tutorials, courses, and detailed documentation. OpenCV is written in optimized C++ code which allows for high-speed execution and a low software overhead.

SimpleCV: SimpleCV is an open-source framework developed by Sight Machine to easily develop computer vision projects. The framework combines various computer vision libraries, including OpenCV, and abstracts many of the low-level details away from the developer. SimpleCV prides itself on making computer vision easy and accessible to everyone (Sight Machine Inc.). The framework is written in Python and available on all major operating systems. SimpleCV has a larger software overhead because it is a framework rather than a single library. SimpleCV does not appear to be under development anymore, but still has a stable release available to download. The documentation, forums, and overall support of SimpleCV are much less useful when compared to the other computer vision offerings that are available.

TensorFlow: TensorFlow is an open-source machine learning platform made by Google to create, train, and implement designs. Tensorflow can be used with C, C++, Java, Go, or Python and supports many of the popular operating systems. Coca-Cola, Intel, Twitter, Airbnb, and other prominent companies utilize TensorFlow (TensorFlow "Why TensorFlow"). One of the main strengths of TensorFlow is the ability to train and deploy custom machine learning models. The software package also comes with many pre-trained models that can also be used.

Although TensorFlow was not designed specifically for computer vision, there is built-in support for computer vision applications. There is support for servers, IoT (Internet of Things) devices, and web devices. There is ample support for TensorFlow with many pre-trained models, datasets, blogs, forums, and tutorials readily available. Since TensorFlow is a collection of machine learning tools, it has a relatively high overhead when compared to some of the other computer vision offerings. The latency of this software package needs to be considered.

TensorFlow Lite: TensorFlow Lite is a specialized version of TensorFlow designed specifically for mobile and embedded devices. This software package is optimized for latency, privacy, connectivity, size, and power consumption (TensorFlow "TensorFlow Lite"). TensorFlow Lite can be used with Java, C++, Python, and other popular programming languages. It supports Linux and many common microcontroller operating systems. This software package requires little space on a microcontroller and incorporates hardware acceleration to boost performance and reduce latency. Similar to the standard TensorFlow, TensorFlow Lite was designed for machine learning but does support computer vision applications.

Nvidia Vision Programming Interface(VPI): The Vision Programming Interface(VPI) is a software library developed by Nvidia for computer vision and image processing applications. This library is optimized for performance on the Jetson Nano line of processors. The VPI supports both C++ and Python programming and is available on most major operating systems. The optimized algorithms in the VPI offer significantly better performance compared to many other computer vision tools and can be up to fifty times faster than similar software packages (NVIDIA Corporation). In addition to being highly efficient, the VPI can be used in conjunction with other popular computer vision tools. Most notably, the VPI easily integrates with OpenCV to quickly produce computer vision applications. The VPI is relatively new compared to some of the other computer vision tools and new versions are still currently being developed. There is not as much community support compared to OpenCV and TensorFlow, but Nvidia does offer a variety of tutorials and a forum where Nvidia developers frequently answer questions.

YOLOv3 (You Only Look Once): The You Only Look Once version 3 computer vision tool is an object detection algorithm that is built upon Keras and OpenCV. This algorithm was designed for fast real-time object detection, but can still be used to process images. The algorithm favors speed over accuracy and has a low accuracy for detecting small objects compared with other commonly used algorithms (Meel). Although newer versions of the YOLO algorithm have improved the accuracy, this software was not further pursued because of the low accuracy for small images.

Keras: Keras is a Python API designed to simplify the use of TensorFlow 2.0 for users. Keras abstracts away many of the low-level details associated with developing in Tensorflow while maintaining all of TensorFlow's benefits. The API prides itself on being simple, flexible, and powerful so that applications can be rapidly developed (Keras). Keras, like TensorFlow, was developed to be a machine learning tool and is used by NASA and YouTube. KerasCV is a subsection of Keras which supports many standard computer vision features such as image classification, object detection, and image manipulation. There is support for KerasCV in the form of guides, example code, forums, and a community supporting the software.

3.2.2.2 Computer Vision Preprocessing

OpenCV is the primary software being used for the computer vision needs of this project. Nvidia's VPI will be implemented if needed to improve the algorithm performance. OpenCV offers thousands of functions that perform a wide range of operations on images and videos. With so many possible options, it is important to narrow down the scope of OpenCV to a smaller number of relevant functions. This section discusses some of the necessary functions for image preprocessing that are needed for implementing various computer vision algorithms.

The initial input for the computer vision subsystem, and the entire system overall, is an image of the current state of the billiard table. The image preprocessing begins by converting the color space of the image from RGB to grayscale. Depending upon the selected algorithm, the image may also need to be thresholded. Thresholding of an image is essentially creating a binary image based on a threshold value. Finally, image filtering may also be needed to remove unwanted noise from the image or to prepare an image for subsequent algorithms. Some, or all, of these preprocessing steps, may be necessary before running object detection algorithms on the image.

Image Acquisition: The first step of all the needed algorithms is to capture the current state of the table. From this image, the position of the billiard balls will be extracted and later used by other subsystems of the project. OpenCV easily interfaces with any type of camera connected to the device on which the program is running. The selected webcam and how the webcam will be mounted are discussed in a future section. OpenCV will be used to control the webcam and capture the image when needed. OpenCV easily allows for the captured image to be saved onto the device in which the program is running.

Color Space Conversion RGB → Grayscale: Many of the computer vision algorithms that OpenCV implements require a grayscale image. By default, the input image is captured in RGB format. The RGB color format is how many images are displayed because it offers a wide range of possible coloring options to give the most accurate color representation of the image. Each pixel of the image will have an eight-bit red, green, and blue component typically displayed as a decimal value between 0-255. The combination of all of these color values is what defines the color of a pixel. While this large amount of color data is useful in displaying vibrant images, it is not helpful when trying to process an image.

To reduce the amount of computation needed, nearly all computer vision algorithms require that the image be converted from an RGB format to a grayscale format. This conversion allows for each pixel to be represented by one eight-bit value. A grayscale value of 0 corresponds to black while a grayscale value of 255 corresponds to white. With a grayscale conversion, all of the RGB-colored pixels of an image are mapped to a corresponding grayscale pixel. Although the color information is lost during a grayscale conversion, the information necessary to perform the computer vision algorithms is preserved. Specifically, the edges, regions, blobs, junctions, and other relevant information are maintained when an image is converted to grayscale (Breckon and Solomon 9-14).

The actual conversion of an RGB image to a grayscale image is simple in OpenCV. OpenCV allows for the conversion of color spaces with a call to the *cvtColor()* function. This function has many different predefined conversions that will allow for the input image to be converted to grayscale. One important detail to note is that the standard color format for OpenCV is BGR rather than RGB, a small modification will be needed to the function call when implementing the color conversion (OpenCV "Color Space Conversions"). The conversion of the initial input image from a color space to a grayscale space is lossy, meaning the initial image cannot be reconstructed easily. For this reason, the original input image must be saved so that it can be used in other parts of the project.

Image Thresholding: Some of the algorithms that OpenCV offers require an image to undergo thresholding before being processed. Specifically, algorithms that detect the edges of images utilize thresholding. Thresholding is a process to break an image into distinct regions of pixels to make images easier to process (Data Carpentry). In a sense, thresholding an image is converting it to binary because all of the pixels will be black or white. This type of image preprocessing is useful because distinct edges begin to form around features in the image which makes more complicated algorithms, like edge detection, possible.

One of the challenges of implementing image thresholding is determining what threshold value to use for an image. The threshold value will be used to determine which pixels are turned completely black and which are turned completely white. It can be difficult to determine an appropriate threshold value because the threshold will depend on the camera, lighting, and other factors that may not always be consistent. A common technique is to create a histogram of the intensities of the grayscale pixels as shown in figure 3.4 (Jayasekara et al. 530). Ideally, the histogram will have a clear distinction of values above and below the threshold. These histograms can be constructed in a variety of lighting conditions and an empirical value can be deduced from the findings.

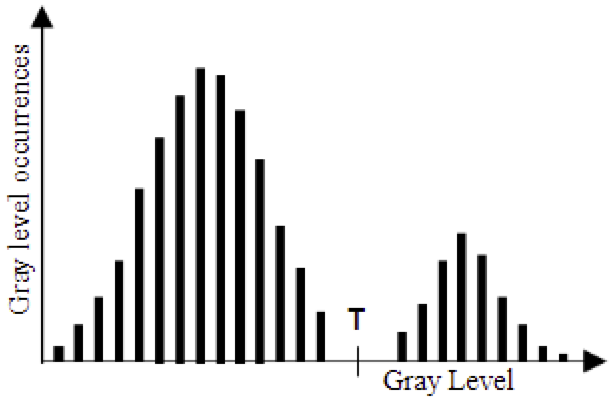


Figure 3.4: Ideal Distribution of Thresholding on Image

Rather than empirically determining the threshold value, Otsu's method can be used for determining the optimal threshold value. Otsu's method works by iterating through possible threshold values and determining which threshold value gives the tightest clustering of black and white pixels (Muthukrishnan). Otsu's method tries many possible options and assigns values to the accuracy of the threshold, the highest value corresponds to the best threshold. While this approach does seem more accurate than the empirical approach, it will still be impacted by varying lighting conditions and will vary depending on where the billiards table is located.

For both previously mentioned techniques, there is one threshold value used for the entire image. The technique of having one thresholding value is called global thresholding. Global thresholding faces challenges when the lighting and picture resolution are not uniform throughout an image. To mitigate these issues, adaptive thresholding can be used. Adaptive thresholding does not use a single global threshold value, but rather compares the grayscale values of neighborhoods of pixels to determine localized thresholds. This approach to thresholding accounts for lighting issues that may make one portion of an image darker than the rest. By using many threshold values, adaptive thresholding can produce much more accurate results and will typically outperform global thresholding techniques. An example of adaptive thresholding on objects of various colors and sizes is shown in figure 3.5 (Rosebrock).

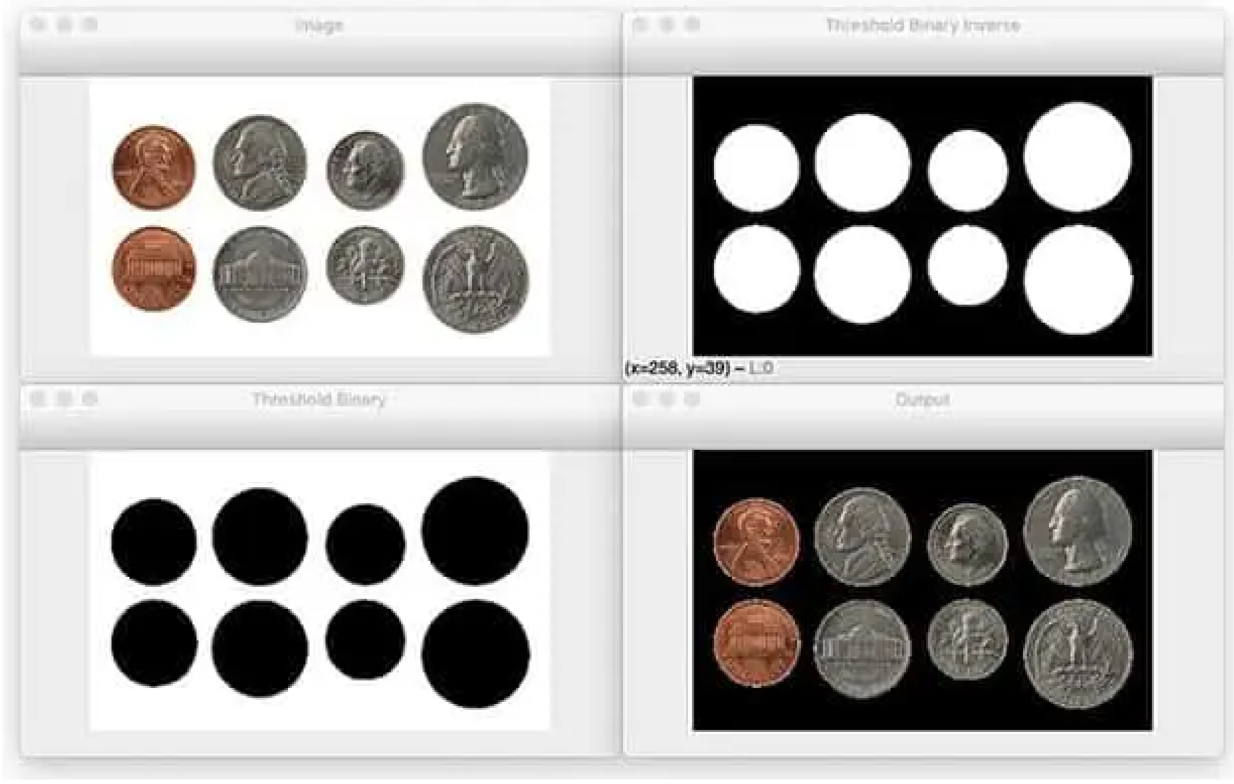


Figure 3.5: Image Thresholding to Isolate Region of Interest

An aadaptive thresholding algorithm is used because of its better accuracy. OpenCV offers multiple different kinds of adaptive thresholding algorithms including adaptive mean thresholding and adaptive Gaussian thresholding. The specific type of adaptive thresholding used by VISION is adaptive Guassian thresholding.

Image Filtering: Image filtering is the process of removing aspects of an image that are not desired to aid in processing the image. There are many different kinds of image filters available and they are most commonly used to remove noise, sharpen the edges, or blur the image together. These various types of filters are used for specific applications and help improve the quality of the final output. In general, image filtering occurs by looking at every pixel in the image and comparing it to all of its neighboring pixels through convolution. All of these pixels are then compared and altered based on the desired type of filtering.

One of the main applications for image filtering is noise removal. Noise, or unwanted additions to images, arises from many different factors related to how images are acquired. Many types of noise removal filters can be applied to images that come at a tradeoff of accuracy for computational complexity. Two of the simpler filters are the mean filter and the median filter. The mean filter is useful for removing uniform noise throughout an image but tends to worsen the image's overall clarity. The median filter is useful for removing salt-and-pepper noise, small regions of high-intensity noise, and is better at preserving the image clarity (Breckon and Solomon 90-94). A more complex filter is the Gaussian filter that can be used to remove noise, smooth an image, or prepare an image for edge detection. The Gaussian filter can be used for a wide range of applications because it allows the user to control a standard deviation parameter. Depending upon the value of this parameter, the filter can be used for different tasks.

Image filtering is also used to enhance an image before being used in an edge detection algorithm. Edge detection filters work by searching for regions of an image where there is a large amount of change occurring between pixels. Conceptually this represents a transition from one aspect of an image to another. Filters that are designed for edge detection locate these regions and amplify these transitions so that they are more easily seen during further processing. There are many different image filters available, OpenCV supports the Sobel, Scharr, and Laplacian filters (OpenCV "Image Gradients"). Overall, these filters are rather similar and most image processing algorithms will specify which filter is recommended to achieve the best results. The algorithm VISION uses for computer vision implements image filtering internally and no additionally filtering is needed.

3.2.2.3 Computer Vision Algorithms

Once an image has undergone the necessary preprocessing, computer vision algorithms can be applied to extract the necessary information out of the image. This subsystem is responsible for isolating the billiards table from the background, identifying the billiard balls and their position, and differentiating between the different colored balls. The following section discusses image processing algorithms that are used to achieve the computer vision goals of this project.

Canny Edge Detection: The Canny Edge Detection algorithm is a popular image processing technique that can be used to extract all of the edges from an image. This algorithm gained a lot of popularity because it was designed to exclude incorrect or misleading edges that previous algorithms tended to include. This algorithm is useful for identifying the billiard balls. A sample image after undergoing canny edge detection is shown in figure 3.6 (BogoToBogo). The table itself will appear as the largest rectangular edge in the image and the billiard balls should be the only circular objects in the image. Using these characteristics, the billiard balls can be detected.

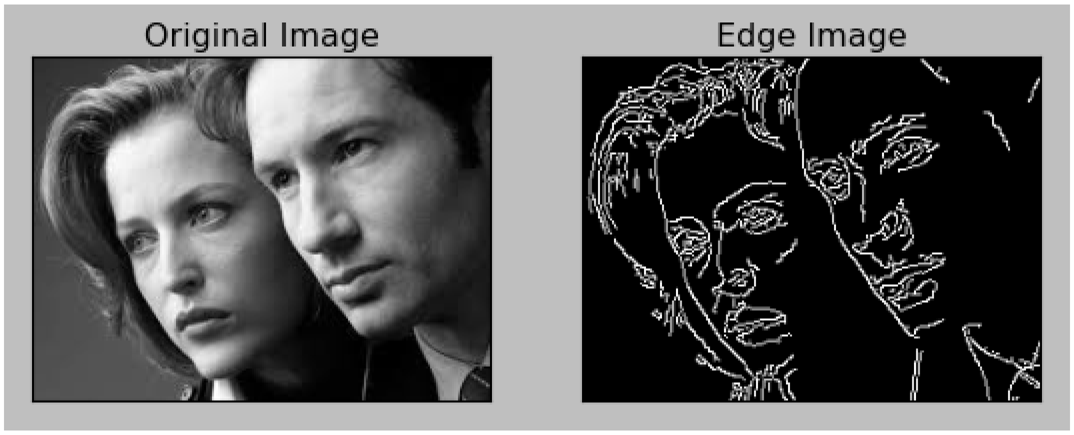


Figure 3.6: Canny Edge Detection on an Image (Awaiting Permission from BogoToBogo)

Canny Edge detection is a multi-step process that begins with filtering the image using a Gaussian filter to remove any present noise. A Sobel filter is then applied to find and magnify all of the discovered edges. The algorithm then checks all of the discovered edges and only allows the localized maximum pixels to pass to the next stage of the algorithm. This process ensures that the returned edges are the thinnest, most prominent edges in the image. The final step in the algorithm is another check of which edges should be returned and which edges should not. A hysteresis threshold is applied to the image. This is a threshold technique where two threshold values are used to identify only the strongest edge candidates and ignore the weaker edges (OpenCV "Canny Edge Detection").

Template Matching: Template matching is a simple, but powerful algorithm for locating specific objects in an image. Template matching works by having a template, or sample image, of the object being searched for. The template begins in the upper left corner of the image and every pixel from the template is compared with every pixel in the input image. The template is then moved to the right by one pixel and the pixel comparison is done again. When the template reaches the end of a row, the template is moved down to the next row. This process, which is known as two-dimensional convolution, is repeated until the template has been compared in every possible location with the input image. Regions of the image that match the template will be assigned a high associativity value and regions that do not match the template will be assigned a low associativity value. The regions with the highest associativity values will be considered matches for the template (Adaptive-Vision).

The template image must be the same size as the object appearing in the input image. The template is being compared in every possible location in the input image. If the template is not the same size as the object in the input image, it is possible that the object will not be discovered or an incorrect object will be detected. Additionally, there are many ways to perform pixel comparisons. Different algorithms implement different pixel matching operations which can impact the algorithm's performance and accuracy. OpenCV implements six different operations which can all be used for template matching. The choice of which operation to use can be decided by trial and error with actual input images to determine which operation works best for the project.

One consideration when using template matching is if an RGB or grayscale image should be used for the input image. Most template matching algorithms, including the one supported in OpenCV, allow for both colored and grayscale inputs to be used. The benefit of using colored input images is that the algorithm will be able to better detect matches of a specific color. The increased matching ability is because there will be significantly more pixel values to compare the template image with. The drawback to using colored input images is that the algorithm becomes more computationally complex because now each pixel has a red, green, and blue component to compare. When using a colored input, the algorithm is essentially run three times, once for each color channel, and the results are averaged together for each pixel (OpenCV "Object Detection").

Template matching would be beneficial to use when trying to identify and localize the billiard balls in the input image. The maximum number and possible colors of the billiard balls being used will be known. Each of the billiard balls can have its own template image and the algorithm can be run for each possible billiard ball. There will need to be some type of confirmation that the object detected by each iteration of the algorithm found the correct billiard ball because some of the balls will not be on the billiards table. This approach also may be too computationally complex and lead to high latency. If the algorithm is run for each possible billiard ball using a colored input image, there will be a lot of intensive computation every time the state of the billiards table changes.

Suzuki's Algorithm (Finding All Contours): Contours in image processing are the lines that join all of the points along the border of some shape or object. Contours can be thought of as the outline of an object that is made between the object and the background. This idea is useful because the expected contours of the billiard balls and the billiard table can be used to detect these objects. An algorithm that finds all of the contours present in an image can be run, and the contours that are found can be filtered to extract only the desired contours.

Suzuki's algorithm, which is implemented by OpenCV, works by traversing the input image pixel by pixel from the top left to the bottom right. The algorithm works by comparing the value of a pixel to the values of the surrounding pixels. For many implementations of this algorithm, a binary image is required. As each pixel is examined, it is assigned a value that can be used to determine if an outer border, hole border, or neither has been discovered (Kang and Atul). These results can then be used to determine what contours exist in an image.

Finding all of the contours in an image is a useful feature, but contours that are not desired will also be found. To be able to successfully implement this algorithm, all of the contours that are found will need to be filtered. Only the contours of the billiard balls should be returned from the computer vision system. The main application of this algorithm would be to detect and localize the billiard balls. For this reason, any contour that is not a circle can be ignored. It is possible to approximate all of the contours to common geometric shapes by using the *approxPolyDP()* function in OpenCV. The number of edges present in the contours can then be compared to the expected values. The contours of the billiard balls should have more than eight edges (more than eight edges represent a circular shape) (Authentise).

Further filtering can also be implemented to ensure that the contours that are found are also of the expected size. A minimum and maximum size for the billiard balls was determined so that is unlikely incorrect contours are reported. OpenCV supports finding the area of a contour as well as contour highlighting. Contour highlighting can be used to view what contours are being discovered and adjust the filtering portion of the algorithm as needed.

Suzuki's algorithm would be useful in locating the billiard balls from the input image. Although this algorithm will likely return contours that are not wanted, OpenCV offers many ways to sort through the contours and extract only the relevant objects. This approach allows for a user to place tight guidelines on what objects are detected but requires testing and refinement to ensure that the filtering parameters are correct and reliable.

Hough Circle Transform: The Hough Circle Transform is a computer vision algorithm that can be used to detect all of the circles in an image. This algorithm allows for circles of a certain radius to be discovered in an image. All other shapes and any circles that have a radius that is either too big or too small will be ignored by the algorithm. This algorithm is relatively accurate and can ignore most shapes that do not fit the search criteria.

The Hough Circle Transform works by utilizing the characteristics of circles. All circles will have a center and some radius that is fixed for any point on the circle. Consider some arbitrary circle *c* with radius *r*. This algorithm works by traversing the perimeter of circle c and essentially drawing a circle, still with radius *r*, at every point along the perimeter. There will be one point of intersection in which all of the circles that are drawn while traversing circle *c* overlap with each other (ImageJ). This point will be the center of circle *c*. Every intersection is awarded a point and the center of the circle will have a very high point concentration compared to the surrounding pixels. The algorithm uses the point concentration relative to the neighboring pixels to determine if there is a circle present.

Many implementations of the algorithm require an outline of the objects being searched for in a binary image format. This requirement can easily be met by using the Canny Edge Detection algorithm discussed previously. The outlines in the image are what form the perimeter to be traversed by the Hough Circle algorithm. By using the outline of the objects it is also possible to detect overlapping or touching circles as well like shown in figure 3.7 (Sinha). If two circles are overlapped, the perimeter will form a shape that looks similar to the number eight. As the transform traverses the perimeter, it is often able to detect both circles, assuming they are of the same radius. This feature is because two centers will be found that have high concentrations of overlapping pixels compared to the rest of the image. The image below depicts when two overlapping circles of the same radius are detected.

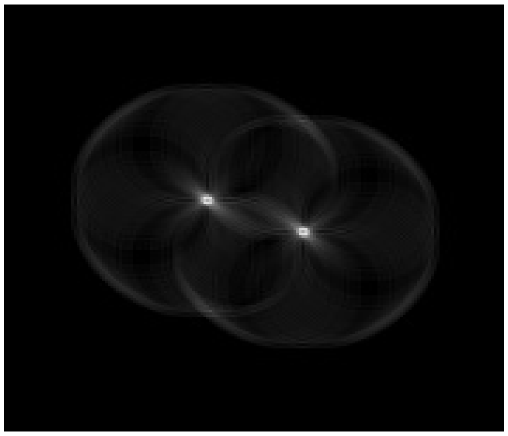


Figure 3.7: Detection of Overlapping Circles

Similar to Suzuki's algorithm, unwanted circles may be found by the algorithm. Filtering of the circles found by the algorithm may be needed to ensure that only the billiard balls are detected. Fortunately, OpenCV's implementation of the algorithm allows for the minimum and maximum radius to be specified. The optimal values for these thresholds will need to be determined experimentally. Further filtering can be done by checking the color of the discovered circles to ensure that it is an expected color.

The main application of the Hough Circle Transform would be identifying and locating the billiard balls in the image. This task is one of the main goals of the computer vision subsection, and this transform looks very promising to accomplish the goal. One other related application would be identifying the pockets on the billiards table.

Douglas-Peucker Algorithm (Contour Approximation): The Douglas-Peucker algorithm is used to approximate complex contours into simpler contours. This algorithm essentially takes a detailed contour and simplifies it into a geometric shape such as a triangle, square, or similar shape. An examples of the contour simplification is shown in figure 3.8 (OpenCV "Contour Features"). The amount of simplification applied to a contour typically depends on an input parameter, epsilon, as well as if the expected simplified contour should be a closed shape. The algorithm works by determining the starting and ending points of the contour. The edges between these two points are what will be simplified. The algorithm uses the epsilon value to compare the distance from each point on the contour to a reference line. Points that become smaller than the epsilon value are discarded and those that are larger than the epsilon value are kept (Lee).

The value of epsilon used in this algorithm is crucial to what type of contour will be detected in the image. In the figure below, the leftmost image is the input image. The green outline in the middle image shows the discovered contour for an epsilon value of 10%. The green outline in the rightmost image shows the extracted contour for an epsilon value of 1%. As the value of epsilon decreases, the more tightly the modified contour will resemble the actual contour.

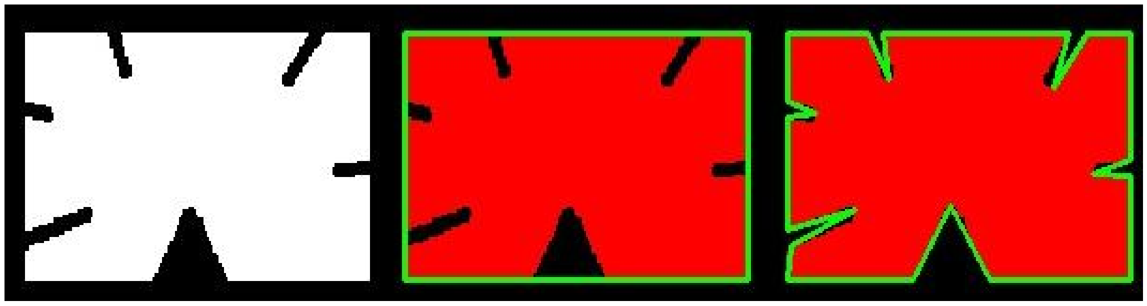


Figure 3.8: Epsilon Value on Algorithm Output

Like many of the other algorithms discussed, the Douglas-Peucker Algorithm requires a binary image as input. Furthermore, the algorithm requires that all of the contours in the image have already been discovered. These requirements can be accomplished by using previously discussed functionalities supported by OpenCV such as thresholding and the Canny Edge Detection algorithm. The value of epsilon to use will need to be determined experimentally, but will likely be relatively high because the billiards table is nearly a rectangle.

3.2.3 Visual Impairment Assistive Technology

Visual impairment is not something new to humanity. Individuals who suffer from this setback have learned to adapt to the setback for generations, but only in the last century has technology rapidly accelerated this progress to such an extent that life can gradually approach normality for those affected by visual impairment. To best guide this project's goal of assisting impaired billiard players, several previously designed assistive technologies are examined. What is examined for these compatible deliverables is a user interface that is able to be navigated either solely by touch or sound and a guidance system that utilizes sound or sensation to prompt a user toward a desired direction or specific location. There are several cases that are outside of the scope of assistance in this project. These include setting up the preliminary orientation of the balls, location of the user's cue, and obstacle avoidance.

With the constraints of the assistive technology outlined, two primary interfaces must be examined for the assistive technology deployed in the project: guidance and communication interfaces. The user interface seeks to communicate in ways that enhance the ability for mild impairments to be able to see options - an easy to use, simple, and observable user interface that can be deployed in the case of a fully impaired user. Screen readers and voice technology have become commonplace in much of the technology that is now deployed that will read out what is displayed and highlighted on a screen. Within a similar realm, screen magnification softwares are deployed across devices for users that may have mild visual impairment ("Assistive Technology for the Blind (AT)"). System settings that perform these actions can be a verbal and visual enhancement for a user when navigating a settings page, attempting to start a game, or understanding the layout of a table and specifying the outlined shot. Additionally, braille keyboards and critical buttons are an age-old communication method that can be deployed for the completely blind to communicate with a device when fully powered off.

In terms of user guidance, the project will require methodology that tracks the user and deploys instructions that will locate the user at a desired destination for the optimal shot. Although the project is focused on a specific focus, previously designed technology validates possible options for the desired system and can give insight into how the project's goals can be realized. Localization algorithms such as visual-inertial odometry (VIO) utilize smart phones with a combination of computer vision software and the device's internal measurement units (IMUs) to understand a user's orientation and their current trajectory. Previous research in this realm utilized common benchmarks within a predetermined area to give a relative understanding of their location in a 2-D space. Given the inputs from the camera and the acceleration recorded within the IMU, the device could garner an accurate understanding of the user's location and guide them accordingly through an area that is previously known (Fusco and Coughlan).

Other research breaks down closer to the deployed microcontroller level of localization. A proposed system from Middle Technical University utilizes a IoT machine-to-machine protocol called ZigBee to localize a user relative to several anchor nodes in a room, and an RFID is used to recognize the interior the user has entered (shown in Figure 3.9). The system also scales for wider navigational purposes by using GPS to localize the outdoor position of the user, and alternates between the two depending on location ("Localization Techniques for Blind People in Outdoor/Indoor Environments: Review").

Some visually impaired assistive systems rely less on user localization and more on environmental surroundings. The Sanjivani College of Engineering explored a command based audio input and output assistant that utilized camera inputs and a chatbot functionality to relay meaningful information to the user of their surroundings. The system consisted of a camera, headphones, and a microphone with several core functions including face and emotion recognition, image captioning, object detection, reading, and interfacing directly with a personal assistant bot. This system was fully local to the user and navigated based on user pronounced commands and the inputs given by surrounding by use of Python APIs and computer vision software and then relayed meaningful responses by means of Google's text to speech platform gTTS ("Smart Guidance System for Blind with Wireless Voice Playback").

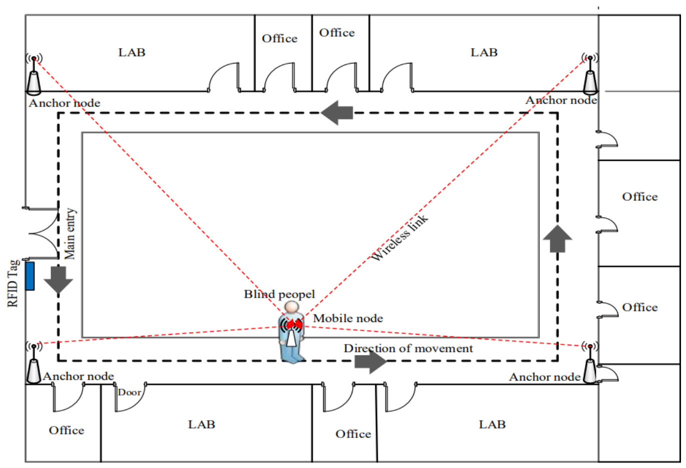


Figure 3.9: Previous System Indoor Localization Design ("Smart Guidance System for Blind with Wireless Voice Playback")

Another smart guidance system relies on several different approaches for determining critical obstacles, determining important events, and delivers audio feedback messages to the user. The Sri Sairam Engineering College developed a system deploying a voice feedback system for navigation that utilized an ultrasonic sensor to safely avoid objects and utilized a MEMS accelerometer for the purpose of understanding the user's dynamic location in a 3-D space. In addition to an accurate portrayal of the user's location, the static location was also understood using this accelerometer and a message was sent to points of contacts in the possible case of an emergency occurring. GPS was used to record the known location of the system and user, and would communicate the location in case of emergency ("Smart Guidance System for Blind with Wireless Voice Playback").

As audio assistive systems are a widely deployed approach, the subsystems for many past projects are a key point of interest for how to read in information and the different data points they focus on. Sensors for navigation can span many technologies. Deploying technologies in conjunction with one another enhances the full picture of the scope of the user's surroundings. For instance, many systems focus on deploying the commonly conjoined ultrasonic sensors and RFID readers to navigate premapped areas and avoid obstacles throughout those regions ("Audio guidance system for blind"). On the other hand, technology such as LiDAR has shown to be viable in the past for the visually impaired ("Voice Navigation Based guiding Device for Visually Impaired People") and can be viewed as a more independent sensor system that is powerful in the full picture it can paint for a system software.

Previous iterations of visual impairment assistive technology lay a good framework for how to best guide users in the scope of navigating a billiards game. User guidance, control, and safety are the primary goals of the system. Emphasizing these by enhancing the ease of use can be best improved by seeing where these projects examined shortcomings and seeing where they can best be improved upon. The following sections research some of the required technology for user interaction to be possible in greater detail.

3.2.4 User Localization

This section describes different technologies or avenues that can be explored for user detection, including but not limited to visually impaired users, technology that could be used in further sections when considering determining the path for the user to the object of interest. The current scope of research is to find how to implement three different features for the user. Further sections will describe which features will be implemented and in which way each of the features will be implemented. This section outlines the process of how to navigate the user around the table to the right position and orient the user is the direction needed to make a shot based on the shot selection algorithm's output.

To do any of the navigation accurately and safely, a proper localization mechanism must be deployed so the user can receive instructions that correspond with their location and heading in real time. Several variables are considered and must be prioritized accordingly for end design selection across various sensors and the corresponding algorithms that can be deployed with them. Variables to consider for each method of sensing revolve around: accuracy, calibration techniques, computational bandwidth, resolution, range, outstanding environmental factors, cost, ease of user integration, scale, materials required, and the method of sensing (i.e. proximity, motion, image, etc.) (Into Robotics).

Hence, here, we examine different technologies, such as RFID and infrared/ultrasonic sensing and ultimately summarize the options and determine what sensors or sensor technologies are selected and in which matter they will be interfaced in the final physical design described in later sections.

Summary of Requirements:

- Latency of the user localization does not exceed 10 seconds
- Accuracy of the user localization is within 1 foot of the true location
- Localization should work independently of the surroundings

3.2.4.1 RFID And Bluetooth

RFID: RFID (Radio Frequency Identification) is a form of wireless communication using radio frequency (RF) waves to identify objects uniquely. RFID systems consist of scanning antennas, transponders, and transceivers. Transceivers and antennas can be combined in an RFID reader. Transponders are typically RFID tags. In practice, mobile or physically mounted RFID readers are located within the region of application transmitting waves within the RF spectrum. The waves are picked up by the RFID tag(s) which will send the signal back to the antenna portion of the RFID reader, a signal which will be turned into data and positioning information. The range of applications depends on the type of RFID readers and tags and the RFID frequency of operation. Table 3.1 summarizes the different types of RFID systems based on the frequencies of operations.

RFID System	Frequency Range	Common Frequency	Operation Range	RFID Tag Pricing
Low-Frequency (LF) RFID Systems	30KHz - 300KHz	125KHz - 134KHz	≤ 10cm	\$0.5 - \$5
High-Frequency (HF) RFID Systems	3MHz - 30MHz	13.56MHz	≤ 30cm	\$0.20 - \$10.00
Ultra High Frequency (UHF) RFID Systems	300MHz - 3GHz	433MHz, 860MHz - 960MHz	≤ 100m	Depends on Active vs Passive Tags

Table 3.1: Comparison of RFID Technologies

These systems not only determine the range of frequency and application but also narrow down the options for tags and readers given that in most instances, the specific type (LF, HF, UHF) of RFID tag can only be read by the same type of RFID reader. LF and HF systems are typically used for close contact applications due to their short range of detection and limited speed, as in ticketing systems, payments, or access control.

VISION would have to rely on either Ultra High-Frequency or High-Frequency systems to locate the user from the edge of the pool table depending on how far away from the table the user is located. 30cm could be sufficient in some cases, but Ultra High-Frequency systems would be a more reliable approach in this case. If this solution is used, the applicability, availability and price of either one of these two solutions will need to be further evaluated. Now that the choice of the RFID system is determined, the next step will be selecting which RFID readers and tags would be suitable for VISION.

RFID Tags: As earlier mentioned, RFID tags consist of the transceiver, an antenna capable of receiving and transmitting signals, but also the RFID chip, which stores the tag's ID. For UHF RFID systems, there are three different types of RFID tags: passive (solely powered by electromagnetic waves), active (powered by a battery), and battery-assisted (combination of active and passive). The latter two allow achieving much longer ranges, at the cost of a much higher price per tag. Other considerations in selecting the proper tag are described below:

- Size: The larger the size, the longer the read range. However, this size is limited by the size of the object being tagged, in this case, our physical design or other objects, which incorporates the tag.

- Alignment and orientation: Ideally, the tag should be aligned in the same plane as the RFID reader to maximize the absorption of RF energy. Testing, if needed at this range, will need to be done to find the proper alignment for the reader and the tag. Additional readers may be positioned in the room of interest if needed to minimize issues arising from this.

- Application-based type: Depending on the vendor, RFID tags are broken down into different categories including hard tags, wet and dry inlays (paper tags with or without adhesive), sensor tags, high-temperature tags, and embeddable tags, among others.

- Resistance to impact, vibrations extreme temperatures, UV, dust, or other chemicals

For this specific application, wet or dry inlays will be the best option considering the cost and the fact that there is no necessity in a bigger or more complex design for our tags. Singular tags or multiple tags can be placed upon the physical design worn by the user, on different sections of the table. An apt example would be Avery Dennison's AD-172u7 inlays which feature a 22 x 12.5 mm antenna designed to operate at around 860-930 MHz, each inlay factory locked with a unique 48-bit identification number while sitting at a total pitch of less than 2 inches. ("UHF RFID Inlay: AD-172u7 - Avery Dennison"). The AD-172u7 is shown below in figure 3.10.

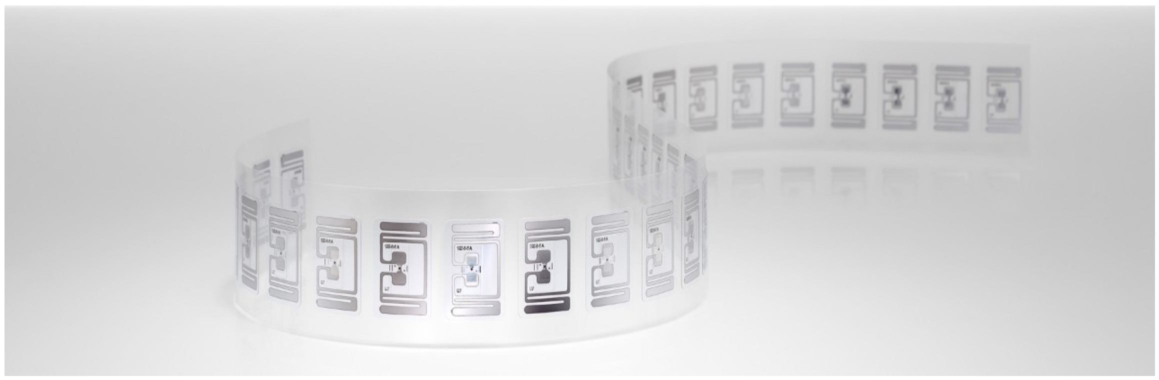


Figure 3.10: AD-172u7 UHF RFID Tag and Inlay

RFID Reader: As earlier mentioned, RFID readers are responsible for sending signals to and receiving signals back from RFID tags. The two main types of RFID readers are either fixed or mobile, further subdivided based on the RFID system in play. Moreover, RFID readers can be further divided based on connectivity options (Wi-Fi, Bluetooth, Serial, USB, LAN), number of antenna ports, power, and processing options. RFID antennas are typically also necessary in addition to RFID readers, since they help convert the RFID reader signal into RF waves that can be picked up by the tags. The antenna will have to be in the same plane or polarity and orientation as the reader to superimpose instead of nullifying their actions. RFID antennas could also be used to facilitate communication between the antenna and the RFID reader. If used for moving the user around the table, the RFID reader would need to be able to distinguish tags that may be placed in very close location since the user holding a tag might have to be in close contact with different tags placed around the table (if any). If this solution is implemented, the choice of RFID reader will need to take this issue into account.

RFID Applications: The most accurate way-finding technologies used for visually impaired individuals these days rely on RFID technology. Despite how relatively inexpensive RFID tags (mainly inlays) are, the biggest cost in these come from RFID readers whose cost vary from around $200 to ten times that or more. Justifying the use of RFID and RFID readers for user identification would involve using RFID for user positioning as well. Other technologies rely on HF RFID systems and make use of (near field communications) NFC which does not need a separate reader, smartphones can serve as a reader for NFC, but are limited to about a few centimeters and typically operate on identifying one tag at a time making them unsuitable for identification or way-finding of visually impaired individuals. Another justification for the use of RFID would be with multiple user detections, where a system of RFID detectors or readers can be positioned at different points in a building identifying and detecting the positions of users with specific RFID tags.

Related to user navigation around the table, there are cases were RFID tags are being used in the dining industry allowing waiters to find guests at the right table based on the specific location returned by an RFID tag preemptively given to them. In a similar way, VISION should be able to differentiate different positions that would correspond to a grid breakdown of what the pool table looks like and know exactly at which position, that is at which RFID tag the user is currently located at. Alternatively, simply detecting the user's position using their RFID tag and use different ways to relate that positioning to the targeted position determined by the algorithm without using additional RFID tags to confirm that the targeted position has indeed been reached.

Bluetooth Low Energy (BLE): A considerable alternative to using RFID technology would be relying on Bluetooth low energy (BLE) systems to achieve the same functionalities described earlier. BLE is a radio frequency technology for wireless communication that can be used to detect and track the position of different objects or people. They operate in a range similar to regular Bluetooth (about 2.400–2.4835 GHz) comparable to Ultra High Frequency RFID systems. The *low energy* name refers to its low power and current consumption (0.01W to 0.5W versus 1W reference for regular Bluetooth and <15mA of current consumption).

BLE localization typically uses BLE beacons placed at specific points in the area of interest, providing information on the specific location of different objects in the area of interest or breaking down the overall area into specific grid locations. These beacons are small, versatile Bluetooth transmitters which broadcast signals at regular intervals. These signals can be detected by wireless devices such as BLE enabled smartphones. This describes a major advantage of BLE versus RFID. The overly expensive RFID readers can be replaced by regular smartphones that natively support BLE. However, the major issue described when using RFID tags in close proximity would still be an issue for this application. The efficiency of this technology will differ when considering different factors like the beacons not transmitting information to the reader synchronously while the user is in motion, or the reader struggling to detect closely placed beacons.

BLE Localization Techniques: Different localization techniques also come into play depending on the application or use case of these beacons. The simplest one would be localization based on the random detection of transmitters or beacons. In this technique, the position is based on which beacon provides the strongest signal back to the reader. Similar to RFID tags, VISION would need to store information about the different beacons to determine the location of the closest beacon to our user. The strongest signal would be calculated by a combination of three different values. The first one is a received signal strength indicator (RSSI) value, which indicates how strong the signal reaching the mobile device is when the beacon is detected by a device or reader. In addition to this, different beacons would broadcast their signal at different transmission powers TX. A combination of the RSSI value and the TX power value must be used when estimating the distance to the beacon. The TX power value is a factory-calibrated, read-only constant that indicates the strength of the signal measured at 1m from the device. Another consideration is a constant, say N, which represents the path loss index and is dependent on the localization environment. Some different values of N are: 1.4–1.9 for corridors, 2 for large open rooms, 3 for furnished rooms, 4 for densely furnished rooms, and 5 between different floors. Using these values, one can calculate the distance based on the following formula:

$$d = 10^{(TX - RSSI)/10n}$$

The major issue with this approach is that this localization technique varies greatly depending on the area in which it is been used (denoted by the range of values for N). Single measurements from the different beacons could consider one as the strongest signal at a particular moment, but measuring it again would lead to another beacon being deemed the strongest signal. A solution for this could be implementing an algorithm that uses a moving average over a period of time. This could introduce a longer time for detection depending on the scanning interval and scanning duration used for the algorithm. Once might consider increasing the frequency of detection while reducing the scanning interval, but this would contradict the point of having a diverse average to get the most accurate outcome. Research done with beacons closely packed under this technique has also shown that when placing them close together - for instance at 25 cm - the accuracy of detection is below 50%, detecting the wrong beacon or transmitter more than half of the time. (Cannizzaro)

Another concern that would have to be investigated in the physical design, is the effect of obstacles around the user. The RSSI values are affected depending on different obstacles or objects in their vicinity. Depending on the density of the obstacles, it has been shown that some detections from the beacons might be lost, and the RSSI values may have a range of error of about 5% which in a narrow area like the pool table could lead to faulty measurements of where the user is accurately located.

Another more accurate, but complex, localization technique is trilateration. Trilateration determines the location of the object or person of interest by using three strategically placed beacons. The beacons draw out a circle, with the beacon at the center of the circle, in their location, and the intersection of the circumferences determines the exact position of the object of interest. Data from each individual beacon allows the system to have a general idea of where the object is located within the beacon's drawn out circle. This location comes with a great range of error. The location of the object due to the second beacon allows some of this error to be removed by placing the object in the overlap of those two drawn out circles, reducing the plausible region where the object would be located. The third beacon would in turn reduce this area to a single point, giving the exact location of the object. The horizontal and vertical positions of the objects are then determined based on the radii of the circles and the distance between the beacons. Those distances are calculated based on RSSI and TX as earlier described. A simple trilateration example is shown below in figure 3.11.

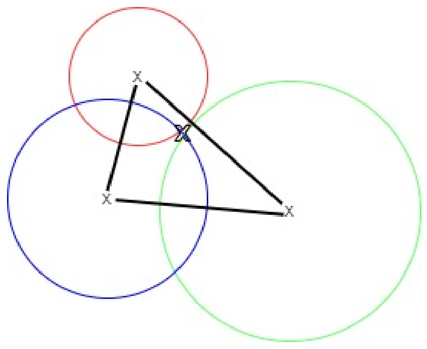


Figure 3.11: Simplified Model of Trilateration

Regardless of the method used to determine the exact position of the user, it might be worth finding ways to minimize the error incurred in the RSSI measurements, which is the basis of the whole process. The moving average described for successive measurements earlier is one of approach but can be improved by smoothing the RSSI values even more. Different models, such as exponential moving average, or weighted moving average, could be introduced such that the RSSI value is not just a simple average of the previous values, but gives greater importance to newer values versus older values. This would help with cases where the user might be in constant motion around the table or in the room. Consider RSSI_n to be the current RSSI measurement, $\mathrm{RSSI}_{\mathrm{smoothed}}$ is the smoothed calculated value and α is a number between zero and one. A smoothing model is shown below: (Ramirez and Chien-Yi Huang)

$$RSSI_{smoothed,\,n} = \alpha * RSSI_{n} + (1-\alpha) * RSSI_{smoothed,\,n-1} + (1-\alpha)^{2} * RSSI_{smoothed,\,n-2} + \ldots + (1-\alpha)^{m} RSSI_{smoothed,\,n-m+1}$$

With $\alpha = \frac{2}{m+1}$ and m is the number of data points used in the smoothing algorithm.

When it comes to selecting which devices to use, VISION has enough flexibility in its decision for both the beacons (shown in figure 3.12) and the reader. An example of a beacon is the iBeacon from BlueBeam which offers variable TX power options, unique identifiers (UID) such as namespace and unstance IDs (for Eddystone UID) or iBeacon UUID (Universally Unique identifier) and major and minor IDs, advertising intervals, and has an option that allows someone to trigger a broadcast at any time other than its usual advertising cycle. It also supports sending out the advertising frames under different formats that carry different data depending on the application, such as:

- Eddystone URLs limited to 17 bytes in Eddystone format (protocol specification that defines a BLE message format for proximity beacon messages)
- Eddystone TLM packets that can also contain battery information, temperature, number of advertisement frames and time since reboot
- Eddystone UID for broadcasting the ID of the beacon, returning the namespace and instance IDs
- iBeacon, Apple's protocol standard returning the iBeacon UUID corresponding to the business that owns the beacon, minor ID which corresponds to the location of the beacon, and major ID which is a more accurate representation of the location of the beacon

Figure 3.12: Bluecharm BLE Beacon with Motion Sensor

For VISION's reader, any device capable of BLE sensing would be enough. This includes actual readers, smartphones, or microcontrollers with Bluetooth functionalities.

3.2.4.2 Sensors

Ultrasonic Sensors: The main advantage of ultrasonic sensors versus other sensors is their ability to detect any object regardless of the nature of the surface. They are also straightforward to integrate with microcontrollers. Ultrasonic sensors would allow a program to specify a distance that would consider an object as being subject to collision. Additionally, the sensors would provide accurate information related to where a user is and how far away they are from a target. For ultrasonic sensors, the most common range of frequency of the ultrasonic pulses spans from 40-70KHz. This frequency determines the range they can cover and accurately detect. Lower frequencies offer a wider range, which spans up to 11m wide with a resolution of 1cm (or lower). For VISION's object detection and user detection around the table, 1cm of resolution would be enough to detect the user in the table range.

A good example of an ultrasonic sensor (transmitter and receiver) that would fit the design is the HRXL-MaxSonar® - WR™ series shown in figure 3.13. These sensors operate at about 42KHz and can return an output in different forms. The most applicable output of the sensor is a pulse width representation of range with a resolution of 1mm. The range can be extracted using the scale factor of 1uS per mm. It also returns an analog voltage output as a single-ended analog voltage scaled representation of the distance, at a resolution of 5mm or 10mm. The corresponding pin for this output remains at this voltage that directly corresponds to the detected distance. Lastly, it also returns a serial output in an RS232 or TTL format where the distance can read as an integer up to a maximum of 4999mm or 9998mm, depending on the model. Some additional advantages of this series are its low current draw, allowing for a long battery life. Additionally its fast measurement cycles (measurements occur every 50ms on average) are fast enough to detect a user as they move. Table 3.2 below summarizes the different models available in this series ("Datasheet for the HRXL-MaxSonar-WR sensor line").

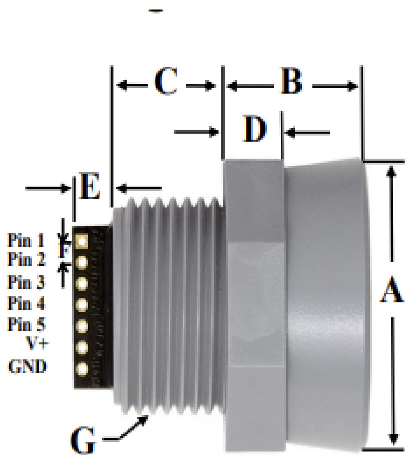
Model Family	**Detection Range**	**Applicatibility**
MB7375 and MB7385	30cm to 1.5m	Wider beam from transmitter suitable for closer distances with a broader detection target
MB7360 and MB7380	30cm to 5m	Provides reliable long range detection zones hence used in tank and bin level measurements
MB7363 and MB7383	50cm to 10m	Higher sensitivity hence great to use for applications where objects do not reflect enough ultrasonic sound such as people detection

Table 3.2: Comparison of Different Ultrasonic Sensors

Based on the above table, the third option would be the most suitable option. The main difference between the MB7363 and the MB7383 is that the serial output for the MB7363 is in the RS232 format versus that for MB7383 is in a TTL format. Both RS232 and TTL (transistor-transistor logic) are forms of serial communication where data is transferred between two parties, a receiver and a transmitter, at a specified baud rate, which indicates the speed of said transmission. The MB7383 using TTL serial communication protocol would be the best option due to the following advantages it has over RS232:

- Less susceptible to noise and other interference
- TTL signals' voltages follow typical microcontroller voltage supply range of 0 to 3.3/5V whereas RS232 signals are +/- 13V, which would require another external power source
- TTL is hence easier to incorporate with microcontroller designs

RS232 to TTL converters are also readily available in case a switch has to be made between these two serial communication protocols.



A	1.37" dia.	34.7 mm dia.
B	0.70"	17.9 mm
C	0.57"	14.4 mm
D	0.31"	7.9 mm
E	0.23"	5.8 mm
F	0.1"	2.54 mm
G	3/4"-14 NPS	
H	1.032" dia.	26.2 mm dia.
I	1.37"	34.8 mm
Weight, 1.23 oz., 32 grams		

Values Are Nominal

Figure 3.13: Model and Dimensions of Compact Housing HRXL-MaxSonar Model

IR Sensors: Compared to ultrasonic sensors which all rely on the time-of-flight principle, other IR sensors use different mechanisms for their functionality. One of which is triangulation. Infrared LED triangulation sensors determine the position and distance from the object using geometric considerations. A collimated laser source (transmitter) is used to illuminate the object to be measured. The light is reflected back (receiver) and focused by a position sensitive detector (PSD) comprising small photo sensors in a row called pixels. The distance is then measured using a ratio of the product of the distances over the size of the detection pixel. The main issue with this approach is its reliance on a different factors lowering its resolution at larger distances. Its biggest perk being the lowest prices comparatively for sensors.

Time-of-flight IR sensors, on the other hand, similar to ultrasonic sensors, operate by sending a light pulse to the object and determine its distance based on the time it took to reach the detector. They have a much longer range than their triangulation counterparts, along with other benefits such as faster transmission and reception times, rapid refresh rate, and lower power consumption. The main disadvantage here is the increase in price and the inability to differentiate targets.

A good option that would fulfill the above advantages without a huge increase in price is the VL53L0X (shown in figure 3.14) from STMicroelectronics whose range of detection goes from 50mm to 1200mm (or 2000mm in one of its function modes) ("World's smallest Time-of-Flight ranging and gesture detection sensor") which is more than enough for collision detection. Its 940 nm vertical cavity surface-emitting laser (VCSEL), is invisible to the human eye. Coupled with internal physical infrared filters offering higher immunity to ambient light, and better robustness to cover glass optical crosstalk. The output can be obtained either using a polling or interrupt mechanism. The default timing for initialization, measurement/ranging and other housekeeping functions it performs is about 33ms. It also uses a streamlined beam that would make detecting a user positioned directly in front of the time of flight sensor much easier. Being a laser-based system, the transmitter sends out a straight line laser and only detects objects in the very narrow beam (25 degrees field of view). Positioning of the sensor would be of great importance when trying to detect a user. Another noteworthy advantage is the low power consumption of about 5-6 µA in standby mode. There are a few other considerations such as the nature of the material and the color of the material which affects the accuracy of the measurements.

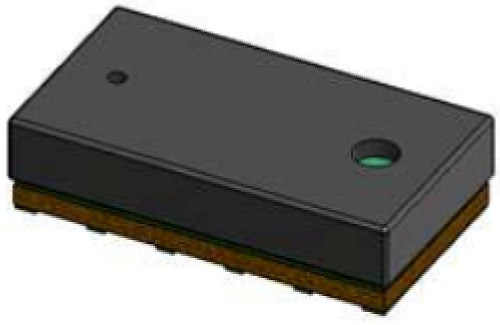


Figure 3.14: VL53L0X Time-of-Flight Ranging and Gesture Detection Sensor

Lighting conditions affect IR sensors while ultrasonic sensors are not affected by this. Ultrasonic sensors are reliant on the shape of the target, struggling with soft, curved, or thin objects while IR sensors work fine under these conditions. Ultrasonic sensors are not easily able to detect sound absorbing surfaces such as clothes or other fabrics hence would struggle to detect human presence in non-ideal circumstances.

3.2.4.3 Localization Algorithms

Sensory input is fundamental for user localization within this project, but the proper algorithms and computational methodology to support the inputted sensory data is key to having accurate data to transmit for proper guidance commands to be sent to the user. Inputs resulting from each sensor type all have the goal of understanding where the user is relative to the billiards table as a whole. To do this, several back end processes can be explored to achieve the desired goal of visualizing the table environment and localizing the user with respect to common data points.

SLAM: In the field of autonomous navigation of robots and automobiles, simultaneous localization and mapping (SLAM) is an improving asset for real time responses to a system's surroundings. SLAM works with sensory imagery primarily from cameras or LiDAR to be able to map the present area and, in the same instance, localize the system relative to the area it navigates through. This goal is best realized through path finding algorithms and object avoidance (discussed further in section 3.2.5), making it a great asset for real time responses of autonomous vehicles for terrain that can not be previously predicted ("What Is SLAM (Simultaneous Localization and Mapping) – MATLAB & Simulink - MATLAB & Simulink").

Maze Array: To do this, constant variables must be set based on the type of interface that is inputting data to this processor. Constants of interest are the size of the table and position of origin point of the sensors and the variable of interest is the changing distance determined between the sensor(s) and the user. With these variables, an accurate localized position in a two dimensional space can be achieved and easily exported with limited size of data being transferred.

In the case of an array being propagated for localization and path guidance of the user, an important distinction to be made lies with the choice on how large each array position is, how accurately to portray the user within these positions, and how many positions deep to make the array. A diagram of such a representation is shown in figure 3.15, where a graphical interface housing the current layout of the billiards table and its accurate physical space would be outlined by a two dimensional array housing the location of a user. Relating to the constraints of such a model and why the variables described above trade offs comes from the desire for accurate real time updates of such an array for both the display and guidance system. Simplistic approaches housing vast approximations for location will be simple to calculate and communicate but risk giving an inaccurate representation that may hinder a user from proper navigation. On the other hand, a very in depth set of data points will add more complexity to the data that is communicated. At such low levels of data communication, lag in communication is not a grave concern and can be considered as lower priority. Specification and ideal frequency of updates to the proper load times is of a higher concern when it comes to efficiency, which is a task that can be optimized within embedded controls.

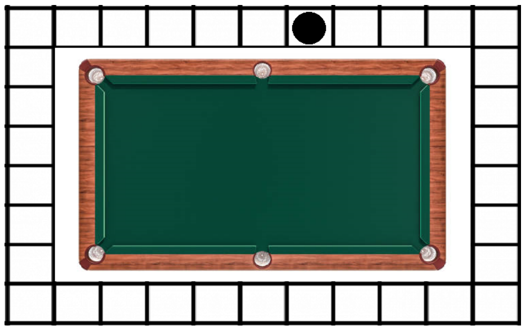


Figure 3.15: Localization Algorithm Array Scheme

More complex localization approaches can also be considered. A three-dimensional space adds significantly greater hurdles to the amount of data that must be communicated, the number of sensors that must be present, and the communication speed of the data. Given the nature of the guidance system and the desire for speed over complex representation, a method such as this may not be optimal for the constraints of this project.

3.2.5 User Guidance

Corresponding with user localization is the outputs to navigate the user to the desired location of the next shot on the table. Previous assistive technology has deployed navigation methods that can be augmented to VISION's desired specifications and constraints. Similarly to the approach for user localization, guidance methodologies carry various pros and cons that can be weighed by comparable variables of cost, scale, accuracy, ease on the user, computational bandwidth, and corresponding algorithms. To explore possible routes for this technology, previous technologies in audio and sensational guidance have been explored and come in varying extents and approaches.

Summary of Requirements:

- System can position user within 1 foot of the desired location
- User is oriented within 15 degrees of the desired shooting direction

3.2.5.1 Audio Outputs

One of the most intuitive guidance systems for user guidance for the visually impaired centers on audio outputs. As mentioned in several previous projects discussed in the visual impairment assistive technology section, voice commands are a very common method of guidance in a real world setting where many unpredictable variables may occur. Alternatively, for the case of navigating a stationary table, simplified methods may be deployed. For instance, audio that is outputted merely to navigate a user by a constant sound in the direction of the destination can house value, and an altering pitch tone could help differentiate the concept of distance from the destination to the user. While these simplistic approaches can seem intuitive to an individual with knowledge of the make of the system, a new user may not comprehend elementary instructions being presented as easily. Applications such as this may require some form of preliminary explanation to the user of how the system operates, while more complicated approaches such as audio commands would in fact be intuitive to the user.

<u>Command-Based Audio Output:</u> Factoring into these audio approaches is the delivery method and density of said method within the system. For an instruction based output, the sources of the output do not necessarily have to be distributed. A centralized location either on the user or in a constant position that emits the instructions is sufficient. However, benefits based on the orientation of the user may arise in having a centralized output of instructions to not confuse delivered instructions. Inconveniences can arise in cases where a central location is emitting sound from a position that is opposite of the direction the instruction is oriented towards. The severity of a case like this is minor in the presence of a robust algorithm that will continue to guide the user based on their adjusting location. A design such as this could also reflect closely with home voice assistant devices such as the Amazon Alexa and Google Home Mini. These devices are recommended to be placed at a central location in the house both for recognizing audio commands and for proper delivery of corresponding outputs. A system such as this realizes two way communication and holds value in terms of the potential to introduce audio commands on top of audio guidance.

A user centered approach as discussed in the previous visual impaired assistive technology section ("Guidance System for Visually Impaired People") discusses the use of headphones for communicating commands to the user. A user based approach can be easily deployed with the latest wireless technology within a Bluetooth headset. Commands can be communicated from a central processor located outside a user and sent via Bluetooth. This decentralized approach to command-based audio eliminates the factor of distractions brought by centralized audio.

In addition to command outputs, the described systems can also be relevant in the realm of relaying outcome information. For instance, in the case of a user conducting a shot, having additional audio that confirms the resulting success or failure could have value to a user that cannot see or visually comprehend what has occurred. This is similar to how previous projects have utilized gTTS ("Guidance System for Visually Impaired People") API for command based navigation or the use of the same API for outputting the words of a written page ("Reading Device for Blind People using Python, OCR and GTTS"), but the same practice can be extrapolated for any situation. As the number of outputted results has a finite value, this feature can hold value for a user in the command-based model of output as it requires identical materials as need to be present for this system.

Direction-Based Audio Output: In the case of a simplistic audio approach for directional commands, a distributed network of speakers could be deployed across the realm of navigation for a user. This array can be deployed in various manners depending on desired accuracy. In the case of navigating a table, the baseline requirements would settle upon the four corners of the table having speakers to be able to deliver a command for each 2-D direction around the space. This can be made more accurate if speakers are added between corners of the table to better position the user at a desired location. Additionally, the accuracy can be enhanced in the alternative manner of having the speakers emit varying levels of pitch to describe distances. For instance, higher pitch could mean further distance to travel and lower pitch could relate to approaching the desired location. These varying implementations also come with a tradeoff in cost based on a linear increase with the added number of speakers in the array or the cost increase from added complexity of the audio technology.

To illustrate the discussed audio delivery methods, figure 3.16 showcases the hypothetical case of a user attempting to navigate from the upper left-hand corner to a desired location of the table. The three audio output mechanisms are shown within the graphic with corresponding labels and expected commands based on their varying purposes. The array-based output is implemented at the basecase of four corner speakers.

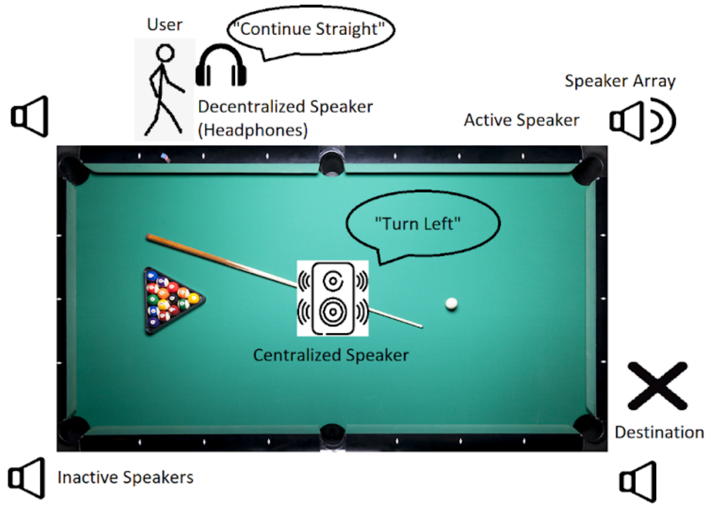


Figure 3.16: Audio Based Navigation Mechanisms

Audio Aim Guidance: Once the user is guided to the proper position on the table, they must then be oriented toward the ball. This mechanism can be deployed in similar approaches as the positional guidance discussed. Within a command based mechanism, real time orientation data is a necessity as corrections to the left or right of the user can only be comprehended if a feedback of data is present. The audio array method comes with the limitation of the same degree if deployed at the base case of four corner speakers. Corrections will also be challenging in this case due to both the wide spacing of the speakers and the algorithmic control of which to activate based on the varying possible positions. To improve accuracy of an array for aiming the user's shot orientation, a denser population of speakers is a simple enhancement. At the worst case, the possible blind spot for shooting position is rather wide, and will lead to challenges with the hand off to the user side apparatus of SCRATCH. To limit this challenge and ease difficulty on the user, a worst case angular error from the desired shot position should be established and then used to determine the necessary density of speakers.

Audio Levels: If audio is used for guidance of visually impaired individuals, audio levels produced should be considered for both the ease of proper distinguishment of commands and for auditory wellbeing and safety of the user. Audio levels should be adjusted after installation within multiple environmental settings to confirm they meet these specifications for the user. Some systems can even be implemented that utilize feedback loops for gain control of outputs with installed microphones. (*Accessible Pedestrian Signals* #) For the case of VISION, this specification does not need to be considered down to a predetermined decibel level, but instead needs to be standardized across all the speakers and adjusted within the validation process of the project.

3.2.5.2 Physical Sensory Outputs

While audio has been explored as a guidance mechanism for users with limited use of their site, an additional sense can be deployed in the sensational awareness of a user's surroundings. Stemming from the use of probing canes for the blind, the technology of physical feedback to visually impaired individuals has grown a great deal with the improvement of technology. Vibrations can now be actively created utilizing haptics to deliver purposeful information to a user that describes actions to take or a direction to move.

Designs like that of Maptic ("Maptic is a wearable navigation system for visually impaired people") shown in figure 3.17 have been deployed in wider variable environments for guidance in everyday tasks. This technology is worn by the user in what appears to be simple accessories but instead is a useful haptic guide for the visually impaired. Optical sensors within a necklace-worn device take in inputs that are then routed through an iOS application that sends signals to each of the wrist feedback devices. These signals can be configured in various manners to transmit information and can also be interfaced through voice control. Systems of this manner are very beneficial for guidance in a changing environment such as the open world, and can be extrapolated for more defined scopes.

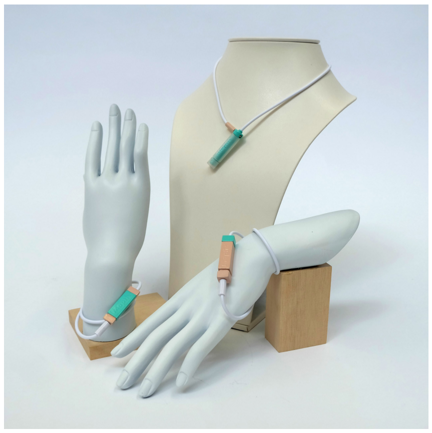


Figure 3.17: Maptic Haptic Feedback Apparatus ("Maptic is a wearable navigation system for visually impaired people")

Within a different scope of problems for the visually impaired, the University of Maryland conducted research into a project giving the blind better ability to parse through reading text off a page shown in figure 3.18. Haptic feedback was used in the study as a manner to deliver information on the page layout and used a camera to take in the text information on the page. ("Evaluating Haptic and Auditory Directional Guidance to Assist Blind People in Reading Printed Text Using Finger-Mounted Cameras") This technology approaches haptics from a different direction, but does show how minimal information transfer from vibrations can be used in conjunction with additional technologies to achieve enhancements in the lives of the handicapped, similar to the goal of VISION.

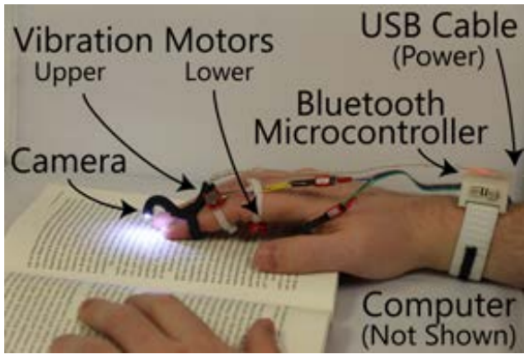


Figure 3.18: Hindsight Haptic Feedback Apparatus ("Evaluating Haptic and Auditory Directional Guidance to Assist Blind People in Reading Printed Text Using Finger-Mounted Cameras")

Within the scope of guidance to desired shot locations on the pool table, commands can be delivered to the user that mean move left, right, forward, backward. As there is no locational specific information being delivered however, this can present comprehension hurdles. A new user may very well misunderstand a command being delivered and struggle to easily follow commands. Additionally, angular orientation of the user creates the need for haptics to require a sort of correction based on this parameter for proper positional guidance. With this variety of commands being delivered in a base level that is binary at the simplest level and can be enhanced with more feedback devices, it can be seen that design can quickly divulge into complication and result in a negative user experience. These factors must be considered in design, especially when weighing options in a static vs dynamically changing environment.

3.2.5.3 Guidance Algorithms

Navigation algorithms that bridge the gap between sensors to output is the glue to a complete navigation system for an impaired user. Algorithmic constraints are examined with the assumption that an accurate user location and the desired location is being polled to the guidance system from the user localized functionality of the system and the billiards AI respectively. The goal of the guidance algorithm will be to locate the best path between these two data points and navigate around obstacles such as the billiards table and camera stand. Obstacle avoidance is a viable feature to explore, but may create significant added complexity to tools deployed for user localization. This being the case, this feature is considered a stretch goal of the project. Once the desired path is determined from source to destination, outputs must be accurately relayed to the user based on the delivery mechanism for user guidance.

2-D Space Traversal: To navigate the table safely, a leading mechanism to realize the system space is a two-dimensional created similarly to a rudimentary maze that outlines the table as a boundary the user cannot navigate through. This can be accomplished by utilizing common algorithms for navigating a 2-D matrix. There are several approaches to realize this goal including including the commonly deployed backtracking "Rat in a Maze" algorithm. The simplest form of this algorithm will continue to test paths in a binary maze where 0 is traversable and 1 is an obstacle until it reaches the desired location. As higher processing power and a shortest path is desired for this test case, an algorithm of this sort will want to find the absolute shortest path between two points and will want to terminate the function as this path is determined to not hinder processing ability. The Rat in a Maze algorithm operates at $O(2^{n^2})$, meaning that a large array will lead to a nontrivial run-time and severely hinder computational speed ("Rat in a Maze | Backtracking-2").

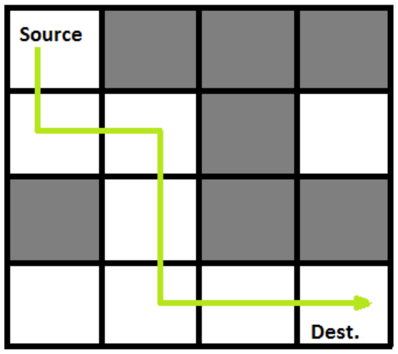


Figure 3.19 Maze Traversal Example

While maze traversal can be a very useful method for complex and changing 2D arrays, the specific use case of VISION brings up the option for an alternative method. As there is a static grid in place that is centered around a constant dimensional table, there are only two available paths that can be taken to navigate the table's perimeter at any given time. With this being the case, a binary guidance algorithm can be deployed, which flows in one of two directions. This approach removes the need for complex computational calculations and puts the strain of the system on sensory input processing.

To deploy the above algorithms, a 2-D space must be accurately created prior to the start of navigation. For this to occur, a constant center point should be established relative to the user. This point can be located at any spot, but must be adjusted accordingly if to have an accurate location of a moving user. The proper state of value of each square of the maze must be set. Recognizing the constants that will not change in this system centers on the billiards table and any added obstacles that may be present within the space. By noting these, the requirement to sense the location of the table is relinquished from the system. Determining the constants would depend largely on added design of the system and dimensions of the table. In addition to these determinations, a determination should be made on the size of each array value. This can be relative to the size of the average human, and can be larger or smaller depending on the expected accuracy of sensors and the desired accuracy of positioning the user.

<u>*Obstacle Avoidance:*</u> If an unexpected object is discovered to be on the floor around the table, warnings and alternative paths can be deployed. The primary limiting factor to this approach is certain deployed sensors will be either robust to these obstacles or their localization algorithms will be greatly hindered. To definitively differentiate between a user and an obstacle, a mixed sensor approach as described in the localization algorithm section would ideally be deployed. In the case where an obstacle is localized, this factor

can be added to the 2-D space as a present array value and algorithms can be deployed to avoid its presence. A system like this can be complex if it requires stepping into a dimension outside of direct adjacency to the table, and would not be compatible with simple guidance mechanisms.

3.2.6 Feedback System

The feedback system will be based on sound in order to accommodate the visually impaired players. The table should give the user feedback on the following events: If a game ball is made, a scratch, if the game is lost, or if the game is won. The table will feature a speaker at every pocket, this will allow the player to be able to determine which pocket the ball went into. The following research is to find ways in which VISION can implement such a system.

Event Sensing: This is the process of discovering if a shot was made by the user. It must also be able to determine if the game has finished or if there was a scratch on the user's turn. There are two main ways in which we would be able to determine if an event has occurred, one is through our computer vision system while the other would be setting up sensors in every pocket.

By employing our computer vision system based on the research in section 3.2 of this paper, VISION will be able to use that information in order to alert the player when an event occurs. This will prove to be higher latency than an approach using physical sensors on every pocket. However, the computer vision algorithm will have to be improved to meet extra requirements. The first requirement is that it must be able to communicate that a ball has been pocketed. It must also allow for detection of a scratch, this means the computer vision system must be able to distinguish the cue ball from the normal ball. Despite these drawbacks, employing the computer vision system to assist in result feedback would offer a major cost advantage, as well as a possible development time advantage.

A sensor based system would allow for almost immediate feedback to the user. The sensor would have to be present within the pocket and be able to withstand a hit from the pool balls. That is not ideal as the sensors will likely be fragile. Some possible options for sensors are a force sensitive resistor (FSR) and an RFID tag.

The FSR would be a good way to detect changes in pressure when the ball falls into the pocket. The FSR works as a variable resistor and an example is shown in Figure 3.20. It has virtually infinite resistance when not pressed. As it is pressed with more force however, the resistance quickly goes down. The FSR has a conductive polymer that allows for the change in resistance when a force is applied. This approach is however not feasible unless the pocketed ball was taken out after the shot has been made. Otherwise the system would have no way of knowing whether or not another shot has been made in the same pocket. One way around this inconvenience would be to keep track of the current value, if it goes up the proper amount for another ball being made, then you could give the user feedback once again. However this will be difficult, as the function for force compared to resistance is not linear.

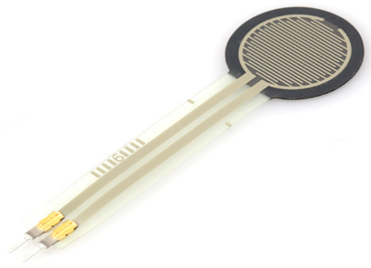


Figure 3.20: Force Resistive Sensor

As discussed in the RFID section, these chips could be placed inside of the ball for the purpose of detecting if a ball were to fall into a pocket. The range requirements would have to be met in a way to ensure that a ball very close to a pocket would not prematurely be counted as a made shot. The other downside of this is that it would likely require a very tedious process to place the RFID tag inside of the pool balls. Doing this without disrupting the natural movement of the balls after the modifications would also require extreme care. A solution using this approach can be found when examining how golf driving ranges are able to track many metrics on a user's shot. By using RFID technology, the user can see the speed of their ball, the path, and the top height traveled by the ball. One such company known as "Top Golf" employs Impinj M700 Series RAIN RFID tag and is shown in figure 3.21. The technology they use is proprietary, however, each ball has a RFID chip that is programmed before the shot is taken, along with a series of sensors in the field in order to gather the metrics previously described. An approach similar to the one taken by Top Golf would be very valuable. However, the room for error on a driving range is many yards, while the room for error on a pool table could be a centimeter. Currently a patent has been granted for using RFID technology to create a score tracking system for the game of pool, but without any commercial offerings or viable demonstrations on the effectiveness of this technology for pool, this may not be a viable approach.

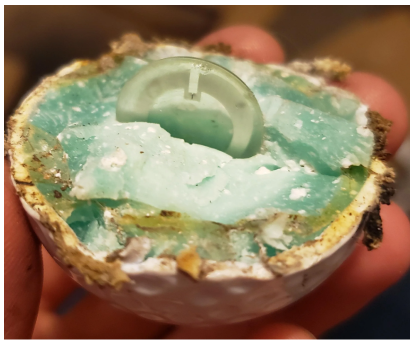


Figure 3.21 RFID Tag Embedded in Golf Ball

Feedback Sound System: The sound system will consist of a speaker located at each pocket. This is to allow the player to orient themselves to the pocket which the ball has fallen into. Some requirements for the sound system are: volume level sufficient to distinguish pocket location from approximately 13 feet away (9 foot pool table with included 4 foot buffer) and six speakers, one at each pocket.

The feedback system must also handle the case in which more than one ball is made. If two or more shots are made into a pocket, the shots will be placed into a queue and announced in sequential order. In the case that an eight ball is pocketed, the system will end the game before further shots will be announced. The edge case in this scenario will be if two balls enter the same pocket, this may be difficult to distinguish based on the range of the RFID technology used. If the technology is capable of detecting two balls in the same pocket, then this case will follow the same queue system. A chart showing the progression of events is shown in figure 3.22.

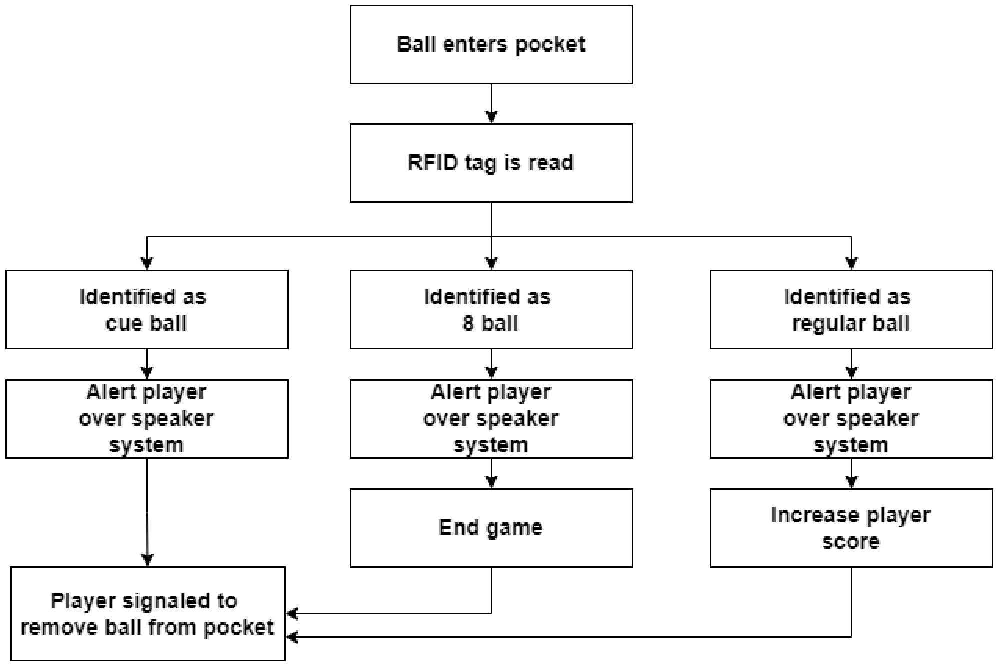

Ball enters pocket
RFID tag is read
Identified as cue ball
Identified as 8 ball
Identified as regular ball
Alert player over speaker system
Alert player over speaker system
Alert player over speaker system
End game
Increase player score
Player signaled to remove ball from pocket

Figure 3.22: Feedback System Shot Results

Determining Shot Results: The feedback system needs to determine what occurred during the player's previous shot attempt. The possible shot outcomes are shown in figure 3.22. In order to determine if balls were sunk during the previous shot, the feedback system will compare the current state of the billiard table to the previous state of the billiard table. The system will determine if the cue ball is present, if the eight ball is present, how many green balls are present, and how many blue balls are present. Comparing the previous table state date to the current table state data will determine which of the five possible scenarios the player's shot falls under. The results of this comparison will determine if the player must continue playing, has won, or has lost. The logic used for this comparison depends on if the eight ball is present. If the eight ball is not present, the user wins if they have no more game balls or loses if they have one or more game balls. If the eight ball is still present, the user continues playing and is notified if they did not make a ball, make their game ball, or make the opponent's game ball.

3.2.7 Direct User Commands

Within this system, the goal is for the user to have as many assets as can be provided for giving them safe and clear access to be able to navigate the pool table and have an understanding of where they are at all times. In addition to system side navigation and localization techniques, commands sent by the user and/or a secondary controller can be explored and implemented when the most benefit to the player can be realized. These commands can be implemented either for critical actions such as designating the end of a turn or focused on enhancing the user experience. For this purpose, previously deployed technology in remote controllers, centralized control, and audio commands are researched for viability within this system. The possible benefits of these designs will have their importance weighed for our system for an optimized user experience.

3.2.7.1 Control Interfaces

The scope of VISION encompasses certain baseline commands that will require user interaction. Whether these commands are relayed from an assistant or the user directly, they will be critical to the performance of the system.

<u>Remote Controller:</u> A possible additional asset for the user within this scope comes in the deployment of a device that stays attached to the user that primarily can be used for setting basic commands of the system. This type of remote controller could also have the added benefit of being accompanied on the same devices that define user localization techniques previously described. Controllers located on a user have been referenced in the section discussing visual impairment assistive technology and additionally correlates to the concept of remotes used for items such as navigating a television interface with touch integrated controls. The latter can be of importance in basic design of remote interfaces for the reason of allowing visually impaired users the ability to have an understanding of and be able to control critical functionality of a system ("Ensure that the remote control can be used without requiring sight"). Remotes such as the one shown in figure 3.23 showcase how a basic interface for control over an audio interface could be made intuitive for a blind user with limited guidance. The simple setup with raised and shaped buttons has been used to relay the intent of controls to users at scale for many years. This importance can be mirrored relative to this system for the needs of critical tasks that a user may need at any point in their performance. A similar design could be extrapolated to use within VISION with proper distinctions of commands in place. For the optimal user experience, having intuitive control directly from the user allows for the quickest response and a superior experience.

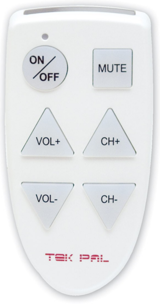


Figure 3.23: TV Remote or the Visually Impaired (“Tek Pal Tactile Low Vision TV Remote Control”)

Centralized Control: In contrast to an interface local to the user, centralized control would require a non-impaired assistant to be in place and be able to relay commands for the current process in place. A centralized interface could be located either on the table, on the side of it, or distanced from the table. This interface would have a focus on buttons or other methods of communicating intent to the primary processor. This could contain critical commands, audio preferences, display settings, etc. While the remote controller is possibly a more optimal method for late stage development of products, a centralized control interface could be a better fit for a prototype to determine where limitations on commands may be. Additionally, having an assistant is most likely a necessity for early stage testing, which would eliminate the benefit brought on by a fully user side interface.

3.2.7.2 Audio Commands

One of the more common features of previously deployed blind-assist technology was the ability for users to communicate their desired system task via voice commands. Previous technology in this field utilized Python speech recognition packages to allow for user commands to be read in and interpreted by a processor and respond accordingly (“Guidance System for Visually Impaired People”). An interface such as this is an advanced feature that has benefits and distractions. The most outstanding benefit of this interface is the ease in being able to ask questions and send commands that is more intuitive than feeling for a proper command on a user side remote and attempting to understand the intent of each button. Additionally, a proper audio command interface would possibly have the ability to interpret approximate ideas from inaccurate commands and comprehend a best course of action. While these factors of ease are valuable, factors of noise pollution both from surrounding environments and from deployed audio guidance methods introduce potent constraints and problems to the system. Issues of this manner can be addressed with proper filtering and close proximity mics, but is a rather expansive problem to combat.

Commands of Interest: Determining the most crucial commands for the use case of the augmented billiards game being deployed in this system requires a weighing of the trade off between the simplicity of the interface and necessity of each command. There is a wide spectrum of possible commands that can be of use to a user and assistant. At a baseline, there are commands required for basic functionality of the game to occur, and others that are more centered on aiding the user experience. Some possible commands to explore include: Center User, Start Game, Shot Taken, Game Status, Begin Navigation, Pause Game, Reset Game. These commands could correspond with responses from a centralized speaker system, begin a guidance system, or allow for a reset process to commence.

3.2.8 Absolute Orientation

For means of getting the most accurate shot direction orientation, designating a position and direction that are defined absolute relative to a given point will allow for the most accurate dissemination for user side system commands. Following the general directional guidance of the user to the proper location, orientation relative to that point is crucial to the user's ability to have a chance at properly hitting the cue ball. To get metrics required to relay this information both to the table and user guidance systems, establishing an orientation relative to a defined orientation is explored.

3.2.8.1 Cue Displacement

The cue displacement will be determined in the shot selection algorithm. The shot selection algorithm already must determine the location of the end of the pool cue in order to verify a shot is reachable. With this information VISION is able to determine the point in space that the user must be located at. Ideally VISION wants to move the user along the edge of the table in order to simplify the guidance system. Therefore VISION will find the intersection of the table with the angle from which the pool cue must be shot. VISION's goal will be to then navigate the user until their pool stick is within the desired range of locations.

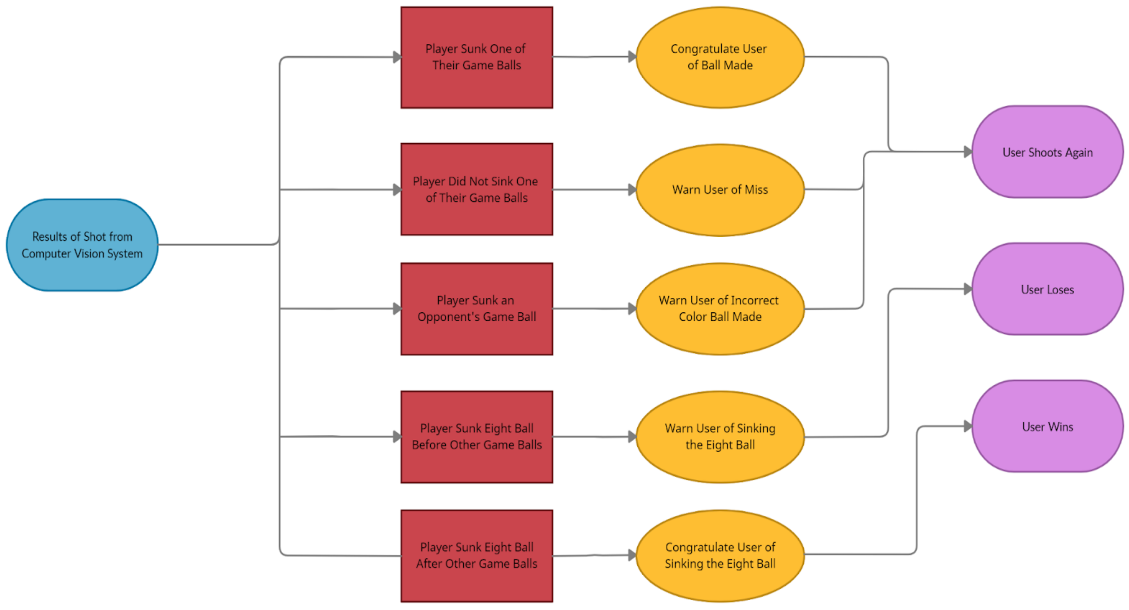
3.2.9 Test Cases

3.2.9.1 Game Modes

Billiards are a collection of games that are played with a billiards table, billiards ball, and cue stick. There are many different games played on billiards tables which include 8-ball pool, 9-ball pool, snooker, four-ball, cushion caroms, and many other variations of similar games. The goal of this project is not to implement all of these different billiards games, but rather to implement a working framework that can be expanded to different applications. For this project, a modified version of 8-ball pool is implemented.

8-Ball Pool: 8-ball pool is one of the more common billiards games played because it is relatively simple and has fewer rules than many other billiard games. 8-ball pool consists of sixteen billiard balls. There is one white (cue) ball, one black (eight) ball, one set of seven solid-colored balls, and one set of seven striped balls. There are two players who each are assigned either solid or striped balls to try and pocket. Each player must use their cue to strike the cue ball in an attempt to push either the striped or solid color balls into the pockets. If a player sinks one of their game balls, they get to go again. If a player does not sink one of their balls it is the other player's turn. If a player sinks the cue ball or one of the other person’s game balls, it is the other person’s turn. If a player sinks the black ball before sinking all of the game balls, that player loses immediately. If a player hits the cue ball and does not hit any of their game balls, the other player gets to move the cue ball within a specified region.

The overall concept of 8-ball pool will remain unchanged in this project, but some small modifications are used to help with the implementation of the project. There will be one cue ball, one black ball, a set of three green balls, and a set of three blue balls. Reducing the number of balls on the table allows for less computation and a faster result for the user. It is reasonable to believe that the project can support more billiard balls at the expense of computation time. Sets of green and blue balls are used rather than solid and striped balls to implement a simpler computer vision algorithm. If the project was to use the standard solid and striped billiard balls, a computer vision algorithm that supports custom object detection would likely be needed. Like regular 8-ball, the player must hit the cue ball to pocket other balls. All other rules above are implemented except when the player cannot hit any of their game balls with the cue ball. Although this implementation is not a true 8-ball game, it is more than sufficient for visually impaired players. Figure 3.24 summarizes the actions supported by VISION. VISION and SCRATCH intend to support a single visually impaired at a time due to budget constraints required with duplicating hardware components, but the systems can easily be extended to two visually impaired players if enough hardware is available.



Results of Shot from Computer Vision System
Player Sunk One of Their Game Balls
Player Did Not Sink One of Their Game Balls
Player Sunk an Opponent's Game Ball
Player Sunk Eight Ball Before Other Game Balls
Player Sunk Eight Ball After Other Game Balls
Congratulate User of Ball Made
Warn User of Miss
Warn User of Incorrect Color Ball Made
Warn User of Sinking the Eight Ball
Congratulate User of Sinking the Eight Ball
User Shoots Again
User Loses
User Wins

Figure 3.24: 8-Ball Features Supported By VISION

The figure above summarizes the features supported by the project. Five possible events are being monitored, each event corresponds with a particular output. If the player sinks one of their game balls, does not sink one of their game balls, or sinks an incorrect game ball, the player will be notified and allowed to shoot again. If the player prematurely sinks the eight ball, they will be notified of losing the game. If the player sinks the eight ball after sinking all of their game balls, they will be notified of their victory. The results of every shot will be presented to the player and spectators audibly through the Swift application.

3.2.9.2 Shots Supported by VISION

The game of pool offers many shot selections besides the conventional straight shot. These different shots exist for several reasons, putting spin on a shot can give you better cue ball placement for the next shot, or a worse position for your opponent. A jump shot, in which you skip the cue ball over one ball in order to hit another is an advanced technique to give you a shot at an angle which no normal pool shot could have achieved. These various shots will be covered in this section in order to determine which will be kept and which must be discarded due to complexity. In order to simplify the distinction of shots, some shot types will be combined which more advanced pool players would recognize as separate shot types. This is due to the complexity of distinguishing between various shot types programmatically.

Straight shot: This is the most common shot where the cue ball has struck in order to directly hit one other pool ball. This is the main shot type which will be calculated. For simplicity this shot will include more advanced shots where the aim is to hit multiple pool ball in order to pocket a ball. VISION will support straight shots.

Bank shot: This is a more difficult shot which involves hitting the cue ball off of one of the rails (The walls of the pool table), and then hitting a pool ball. This shot type fits in with what is achievable within the simulation and shot selection algorithms and will therefore be kept. This shot will also encompass more advanced shots as long as the cue ball is hit off the railing. VISION will support bank shots.

Break shot: This is the initial shot which is taken to start the game of pool. There is not much that can be done to optimize this due to the random nature of the break. When that many different pool balls are placed right next to each other, small differences dramatically change the angles and forces of each ball. Therefore this shot will not be calculated. However it will still be used at the start of the game. VISION will not support break shots.

Jump shot: This shot is created to skip the cue ball over another ball in order to achieve a shot. The simulation and shot selection algorithms will focus on the top down 2D aspects as proof of concept. VISION will therefore not be able to calculate this shot. VISION will not support jump shots.

Spin: This class of shot encompasses many types of shots. Spin can be used to make the ball go almost any direction after a hit as depicted in figure 3.25. This spin is achieved by hitting the pool ball in different locations and with different forces. While VISION could calculate side spin with its current model, calculating spin will be difficult on the simulation as well as on the SCRATCH team responsible for directing the user on which location to hit the cue ball. VISION has decided to cut the added complexity of spin and instead focus on the basic concepts first. In another version adding spin will be of great benefit. VISION will not support spin shots.

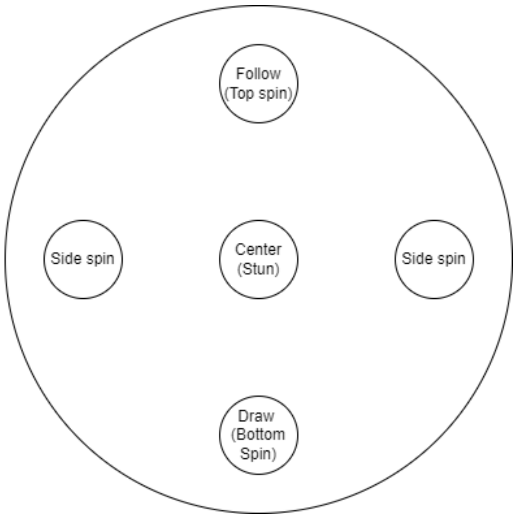


Figure 3.25: Cue Contact Point

3.2.9.3 Physical Limitations

These are constraints brought on by the physical limitations of the pool table, the pool cue, and the physical characteristics of the player. The simulations and shot selection algorithms are generally made for game type scenarios. This means that certain physical limitations are not taken into account. This sectiondiscusses these obstacles and how VISION will overcome them.

Handedness of the user: This will factor into which hand a player uses to play pool. A shot which would be easy for a right handed player to shoot may be extremely awkward if not impossible for a left handed player. This difference is very large and could make a shot selection from the shot selection algorithm completely useless to the user. VISION and SCRATCH currently only support right-handed players.

Length of the cue stick: This limitation ties in with the previous section on handedness. A shot in the middle of the table from the far end will be much too difficult to instruct a visually impaired person to hit. We therefore need a certain limitation on how far the to limit a shot's distance from the user to the cue ball. Giving a shot which the player cannot reach or that the SCRATCH team cannot guide a player to will break the game and therefore must be accounted for in the shot selection algorithm.

Game balls in cue stick path: Shot selection algorithms for many pool games do not factor in the cue stick for a shot. In order to hit a straight shot there must be no pool balls in the path of the cue stick. VISION also needs a small buffer for the players hand as scratching by accidentally moving a ball should be avoided where possible.

No available shot: If the shot selection algorithm is unable to find a safe shot to a pocket, there will be a few options:

- If the user has a ball which can be hit, the ball should be lightly tapped in order to avoid a scratch.
- If there are no good shots to hit one of the users game balls, the shot selection algorithm will respond with a shot that hits 3 railings of the pool table. This prevents a scratch.

White ball pocketed: When the white ball is pocketed, this is counted as a scratch. While VISION may be able to ignore other scratches, where the opposing player gets an opportunity to move the ball, it cannot ignore this one as the ball must have a new placement. In this scenario, the user would have the option to place the ball down onto a certain section of the table, the user must then shoot in the direction of the far wall. This rule would require a completely new shot algorithm that specifically tends to this use case. Not only would the algorithm have to decide the best placement of the ball, but also must find the best shot in a certain direction. Adding this feature would create a lot of work for an occurrence which is not very frequent or important for VISION. Instead a simplification will be enforced. The ball will be placed at the same location that the break will occur and the player will also be allowed to shoot in any direction. Adding functionality for selecting placement and following the rules for a scratch will be very beneficial if not necessary for a competitive game. However, for this proof of concept VISION will instead use the simplified model put forward above.

Other scratches: In situations where the user scratches in ways such as, accidently moving a ball by means of something other than a shot, missing all game balls, or hitting a ball which is not theris first, the shot would normally be turned over to the opponent. In the case of our demo, VISION will instead be allowing the table to remain at its altered state. A new snapshot of the table state must be taken and a new shot selection must be made, the exact way in which the user will signify a scratch to the system will be taken care of by the SCRATCH team, but after that VISION will treat the occurrence as any other shot.

3.2.10 Processing Unit

The computational needs of this project are intensive and require a powerful processor. The processor must be capable of performing artificial intelligence algorithms, computer vision algorithms, image processing algorithms, and various other types of general-purpose computing. For this reason, typical microcontrollers like an Arduino, ESP, or similar device will not suffice. The development boards that best suit the project needs are the Coral Dev Board, the Jetson Nano, and the Raspberry Pi 4 Model B. Although there are many other board offerings, the boards discussed in this section are some of the most highly recommended in the embedded computing community. Table 3.3 summarizes the technical specifications of the three major development boards under consideration.

Coral Dev Board: The Coral Dev Board is a small computer-like board designed specifically for machine learning tasks developed by Google. The board natively supports 2.4GHz and 5GHz wireless connectivity and Bluetooth 4.2. The board uses Mendel, a custom version of Debian Linux, so nearly all common Linux functionalities are available. Most importantly, the board has a built-in Google Edge TPU accelerator capable of 4 trillion operations per second. The board was specifically designed to run Google's proprietary embedded machine learning framework TensorFlow Lite. While the board has excellent performance for TensorFlow Lite programs, the board does not perform as well when trying to implement other types of machine learning frameworks.

Jetson Nano Developer Kit: The Jetson Nano is another powerful computer-like board designed for embedded machine learning applications developed by Nvidia. The board boasts its ability to run multiple neural networks at once to maximize all of its GPU cores. The Nano does not come standard with wireless connectivity or Bluetooth, so additional modules need to be added for wireless and Bluetooth connections. Nvidia utilizes a custom operating system, Linux4Tegra, on the Jetson Nano. Linux4Tegra is based on Ubuntu 18.04 so nearly all of the native Linux commands and utilities will be available on the Nano. Unlike the Coral Dev Board, the Nano is a more general-purpose computing device and can run Tensorflow, Caffe, PyTorch, Keras, MXNet, and many other machine learning software packages. Although the Jetson does not come with a machine learning accelerator, the board is compatible with the standalone Google Edge TPU and can easily be integrated if desired.

Raspberry Pi 4 Model B: The Raspberry Pi line of microcontrollers is one of the most well-known in the embedded community and has a great reputation for being small, yet powerful devices. Unlike the other boards, the Pi was not developed specifically for machine learning tasks but rather as a small general-purpose computer. Despite not being designed for machine learning, the Pi is certainly capable of implementing smaller computer vision and artificial intelligence applications. The board comes standard with 2.4GHz and 5GHz wireless connectivity and supports Bluetooth 5.0. The Pi implements a custom operating system called the Raspberry Pi OS that is based on Debian Linux so it supports a majority of the common Linux features.

Processor	**Coral Dev Board**	**Jetson Nano Developer Kit**	**Raspberry Pi 4 Model B**
CPU	NXP i.MX 8M SoC (ARM Quad-Core)	Cortex-A57 (ARM Quad-Core)	Cortex-A72 (ARM Quad-Core)
GPU	GC700 Graphics Card (Vivante 16-Core)	NVIDIA Maxwell (NVIDIA CUDA 128-Core)	Broadcom VideoCore VI (Broadcom 4-Core)
RAM	1GB or 4GB	2GB or 4GB	1GB, 2GB, 4GB, or 8GB
OS	Mendel (Debian-Linux)	Linux4Tegra (Ubuntu-Linux)	Raspberry Pi OS (DebiDan-Linux)
Wi-Fi	2.4GHz and 5GHz	No	2.4GHz and 5GHz
Bluetooth	Yes (4.2)	No	Yes (5.0)
Ethernet	1GB Ethernet	1GB Ethernet	1GB Ethernet
HDMI	1- HDMI	1 - HDMI	2 - Micro HDMI
USB	1 - Type-A 3.0 1 - Micro-B 2 - Type-C	4 - Type-A 3.0 1 - Micro-B	2 - Type-A 2.0 2 - Type-A 3.0 1 - Type-C
Power	5V DC (USB Type-C)	5V DC (Micro USB or Barrel Jack)	5V DC (USB Type-C or GPIO)
Price	$129.99 - $169.99	$59.99 - $99.99	$34.99 - $174.99

Table 3.3: Summary of Processor Offerings

The table above summarizes the key aspects of the three boards. The most notable differences are in the GPU, Wi-Fi connectivity, Bluetooth connectivity, and price. The Jetson Nano has the most powerful GPU with 128-cores, significantly more than the other boards. The Jetson Nano is also the only board that does not come standard with

Wi-Fi or Bluetooth connectivity. For a high-end development board, it is quite shocking that the board does not have any standard wireless communication features. There is a separate module for the Jetson Nano that includes Wi-Fi and Bluetooth 4.2 available for approximately $20 (Kangalow). The last major difference between the boards is their price. The price ranges of all the boards directly correlate to the amount of RAM chosen for the board. The price for each 4 GB board variation (assuming the Wi-Fi and Bluetooth adaptor is purchased for the Jetson Nano) is $169.99 for the Coral Dev Board, $119.99 for the Jetson Nano, and $99.95 for the Raspberry Pi 4 Model B. Despite having to purchase an additional module to have wireless access, the Nano appears to provide the most value among the devices. During the time of researching processors, there is a chip shortage and none of these boards are available for the retail prices. All third-party and resale boards are approximately equal in price at around $200 each.

Table 3.4 (Franklin) summarizes the performance of the various development boards on common machine learning frameworks. The table below shows the results of benchmark testing on common machine learning frameworks. Although the testing is done using a Raspberry Pi 3 rather than a Raspberry Pi 4, there is no evidence to show that the Pi 4 would have the massive upgrades necessary to outperform the Jetson Nano. The DNR (did not run) entries are indicative of the framework being too computationally complex, limitations in the hardware, or software that is not fully supported. The Coral Dev board performs really well when it supports the TensorFlow framework being used, but it does not support a wide range of frameworks. The Raspberry Pi and the Jetson Nano support a wide range of frameworks, but the Jetson Nano clearly outperforms the Pi across all of the benchmarks.

Model	**Application**	**Framework**	**Jetson Nano**	**Raspberry Pi 3**	**Coral Dev**
ResNet-50 (224×224)	Classification	TensorFlow	36 FPS	1.4 FPS	DNR
MobileNet-v2 (300×300)	Classification	TensorFlow	64 FPS	2.5 FPS	130 FPS
SSD ResNet-18 (960×544)	Object Detection	TensorFlow	5 FPS	DNR	DNR
SSD ResNet-18 (480×272)	Object Detection	TensorFlow	16 FPS	DNR	DNR
SSD ResNet-18 (300×300)	Object Detection	TensorFlow	18 FPS	DNR	DNR
SSD Mobilenet-V2 (960×544)	Object Detection	TensorFlow	8 FPS	DNR	DNR
SSD Mobilenet-V2 (480×272)	Object Detection	TensorFlow	27 FPS	DNR	DNR
SSD Mobilenet-V2 (300×300)	Object Detection	TensorFlow	39 FPS	1 FPS	48 FPS
Inception V4 (299×299)	Classification	PyTorch	11 FPS	DNR	48 FPS
Tiny YOLO V3 (416×416)	Object Detection	Darknet	25 FPS	.5 FPS	DNR
OpenPose (256×256)	Pose Elimination	Caffe	14 FPS	DNR	DNR
VGG-19 (224×224)	Classification	MXNet	10 FPS	.5 FPS	DNR
Super Resolution (481×321)	Image Processing	PyTorch	15 FPS	DNR	DNR
Unet (1×512×512)	Segmentation	Caffe	18 FPS	DNR	DNR

Table 3.4 Performance Results of Benchmark Testing

3.2.11 Communication Methods

Within the scope of VISION is the communication within VISION and the communication with the user side interface (the SCRATCH project team). The communication between these two will be minimalistic in nature to limit the effect of one project on the other. Key variables of interest would be transmitted via either wired or wireless forms of communication. Wired forms of communication are typically more reliable but will require the Jetson Nano (VISION team) and Raspberry Pi (SCRATCH team) to be located in close proximity to each other. Wireless communication is more advanced but is more common in practice. Wireless connectivity may be difficult due to the constraints of device communication on the UCF wireless network (UCF_WPA2).

Ethernet: Ethernet can be used to communicate between the Jetson Nano and Raspberry Pi. Each device can have a statically configured IP address and communicate over an ethernet connection. Both of the devices will be networked together but not be able to connect to any other networks. This approach is simple and reliable but limits the teams by not allowing either device to connect to the internet.

Serial Peripheral Interface (SPI): SPI is a very popular form of serial communication that can be used to interface microcontrollers with each other. SPI would primarily be used to establish a connection from the Jetson Nano to the peripheral ESP microcontrollers. SPI is not likely to be used to communicate with the SCRATCH team because this would require the teams main processors to be physically located together.

Bluetooth: Bluetooth is discussed as a method for sensing user location, however, Bluetooth is also a valuable option for data transmission of variables in the case VISION is looking to suit. Both teams will be using Bluetooth for other transmissions and will have to ensure that the processors can support the number of Bluetooth connections needed. There are many publicly available Bluetooth libraries for Python that can be used. Bluetooth can also be used to connect the Jetson Nano to the peripheral ESP microcontrollers. Bluetooth low energy (BLE) is a form of Bluetooth communication that is slower than normal Bluetooth but also uses significantly less power. Both traditional Bluetooth and Bluetooth low energy are possible communication channels for VISION.

Wi-Fi (TCP Connection): The Jetson Nano and Raspberry Pi can also communicate by establishing a TCP connection to each other and having a reliable communication stream. TCP is the ideal wireless communication protocol for this project because it is supported natively in Python, guarantees delivery of messages, and does not have a large latency. As mentioned previously, the viability of the TCP connection depends upon what the UCF network will allow. Preliminary testing shows that the UCF wireless network UCF_WPA2 does not allow for TCP connections to be established directly between devices on the network.

4. RELATED STANDARDS & DESIGN CONSTRAINTS

4.1 Related Standards

VISION needs to implement many technologies that have accompanying IEEE standards. Some of the most prominent technologies that were used are Wi-Fi, Bluetooth, Bluetooth low energy, USB, micro USB, HDMI, computer vision, machine learning, power supplies, Python, C, MQTT, and UART. These technologies have accompanying IEEE standards that have been researched and documented with findings shown below. The main processor for VISION is a Jetson Nano, so many of the design decisions are based around compatibility and support on the Nano.

4.1.1 Wired Communication Standards

Universal Asynchronous Receiver-Transmitter (UART): UART is a serial data communication circuit that allows for variable data formatting and supports different transmission speeds. Most modern microcontrollers have a UART interface included standard in the serial communication integrated circuit. UART was invented by Gordon Bell of Digital Equipment Corporation in the 1960s (Digilent Corporation). Motorola, IBM, NXP, and other large corporations make a variation of a UART circuit that can be found in various processors and microcontrollers today. There is not a specific standard for UART but rather an agreed-upon format by chip manufacturers to ensure that the basic functionality of UART circuits is the same. The core functionality of different UART circuits will be the same across manufacturers, but additional features and implementation details may vary between manufacturers.

Impact of UART on Design: UART is a powerful communication method that is used program the teams ESP32 and view output from the ESP32. This has been helpful in debugging when developing code for the ESP32 used on the PCB. For this reason, the microcontrollers used by VISION support UART to allow for easier development.

4.1.2 Wireless Communication Standards

Wi-Fi Standards: Wi-Fi has many standards associated with the technology but all stem from the IEEE 802.11 standard. The IEE 802.11 standard governs how nearly all wirelessly connected devices are supposed to function and must be strictly adhered to. The 802.11 standards were released in 1997 and continue to be amended as new advances in wireless technology are created. Although the standard has support for a variety of frequency bands, VISION intends to only use the 2.4GHz band. The 802.11 standards are specific to wireless communication while the 802 parent standard is more generic and involves ethernet connections as well. Wireless protocols are needed for VISION.

Impact of Wi-Fi on Design: VISION will extensively use Wi-Fi or a form of connection to the internet for this project since VISION uses MQTT for the communication between the Swift App (described later) and the Jetson Nano. An internet connection for both has been implemented, tested works correctly, and complies with the 802.11 standards.

Bluetooth Standards: The IEEE 802 class of standards also includes 802.15.1 which was the initial standard for Bluetooth communication between devices. IEEE no longer manages the Bluetooth standards and the Bluetooth Special Interest Group now manages the Bluetooth standard. The current Bluetooth standards require that a manufacturer's device meet specific requirements to market the product as Bluetooth. The widespread adoption and popularity of Bluetooth have led most devices capable of wireless communication to implement some form of Bluetooth. There are several companies that make Bluetooth modules specifically to allow devices to gain Bluetooth connectivity.

Impact of Bluetooth on Design: Bluetooth has emerged as the leading standard for short-range wireless communication between devices. It is assumed that if a device supports wireless communication, it will support Bluetooth (and Wi-Fi) at a minimum. The Jetson Nano does not come standard with wireless communication of any sort. However, the Nano does support a Wi-Fi and Bluetooth module in the form of a network interface card (NIC) that can be connected directly to the motherboard or inserted into a USB slot. VISION uses the USB form of the NIC to provide the Jetson Nano with Wi-Fi and Bluetooth connectivity to communicate with peripheral devices.

4.1.3 Connection Standards

Connection Standards: There are many types of connections that can be established between devices such as GPIOs, USB, micro-USB, USB-C, HDMI, micro-HDMI, 3.5mm jacks, ethernet, DisplayPort, common wall outlets, and various other connection types. All of these different connection types have their own accompanying standards which must be adhered to. From a user perspective, many devices naturally support these connection standards. The VISION team has followed all standards and recommendations for connections based on the industry standards and manufacturer recommendations.

Impact of Connection Standards on Design: The main design consideration for common connections is ensuring that the hardware has enough ports available for all of the necessary components. Tthe VISION team has ensured that the central processing unit can support all of the needed peripherals. The Jetson Nano has a USB-C 3.0 port , a USB-C 2.0 port , two USB 2.0 ports , a USB 3.0 port , HDMI port, ethernet port, and 40 GPIO pins. Although the Jetson Nano comes with a large port selection by default, there were instances when VISION required more USB ports. To deal with this issue the team purchased a USB dongle that turns one USB port into four ports. The single USB port takes input from up to four devices so the dongle specifications were consulted so that the dongle was not overwhelmed with data. The devices plugged into the dongle (mouse and keyboard) have a low enough data rate to conform to the dongle's specifications and works reliability for VISION.

4.1.4 Programming Standards

Python Standards: Python's standard library is very extensive, offering a varied range of facilities such as built-in modules (written in C, others are written in Python and imported in source form) that provide access to different functions depending on the need of the user included but not limited to system operations working on both Unix and Windows based systems. Python also contains many existing programming functions used to solve common issues. Python for Windows includes the entire library as well as some additional components. On the other hand, for Unix like systems, Python comes in as a collection of packages, and additional packages or basic packages may need to be installed with the operating system to obtain additional functions. The library also contains built-in functions and exceptions.

The latest release of Python is Python 3.10.7 released on September 05, 2022. Every release differs from the other by changing any of different syntax features, features in standard libraries or other customer libraries, typing and implementer features, or removing features, deprecating features, and restricting or removing restrictions.

Impact of Python Standards on Design: The Python standards are quite common and well documented. The VISION team has followed all suggested Python standards to ensure that their design functions properly. Deviating from the Python standards can cause undefined behavior in the program and should be avoided. VISION uses Python 3.6 for its access to necessary packages and backwards compatibility with existing software on the Jetson Nano.

C Standards: The latest C standard is ISO/IEC 9899:2018, also known as C17 and the final draft was published in 2018. The biggest issue with using different standards is when a code returns a different output depending on the standard used by the code's compiler. The international standard which defines the C programming language is ISO/IEC 9899, a joint effort of ISO and IEC and the participating countries. The standard is available for easy purchasing online. Each participating country adopts the standard into their own standards system while keeping the technical content the same.

Impact of C Standards on Design: The C standards have been around for a long time and are commonplace with the VISION team. The team followed all C programming standards so that their programs function as expected. Similarly to the Python standards, if the team deviates from C standards, their programs may not function properly. In addition to programs working properly, the C coding standards were followed to ensure that future development on the project can occur with ease.

4.2 Design Constraints

4.2.1 Economic Constraints

The goal of VISION is to make a system that can detect billiard balls, plan strategic shots, determine the best position for a player, and localize and guide a user to the necessary shot position. The purpose of developing VISION is to broaden the inclusivity of societal pastimes to visually impaired individuals. With this in mind, the end user of this project is likely a visually impaired individual trying to play billiards rather than a company trying to make money off the product. The end user will likely have to fund the implementation of VISION themselves, so the project must remain as inexpensive as possible. After the project's completion, the hardware and software designs will be made available to the public, but users will still have to assemble some of the parts themselves. For these reasons, the design must remain cost-efficient and relatively simple so that individuals of all backgrounds can implement VISION.

The components for the project were specifically chosen to meet requirements set forth by the Senior Design guidelines. For example, the Jetson Nano and accompanying Wi-FI and Bluetooth adaptor are needed as a central processing unit because the project must utilize an embedded processor. The software being developed for the project can be executed on any modern computer. An actual user can forgo the Jetson Nano and wireless adaptor for a laptop. This will allow a user to save hundreds of dollars, assuming the user owns or has access to a laptop. Similarly, a user that is interested in playing billiards likely has or has access to a billiards table. Not having to purchase a billiards table takes hundreds of more dollars off of the total cost to implement the project. By excluding two of the most expensive portions of the project that a user likely has already, the project can be implemented for under $200.

The scope of the project is relatively large given the time constraints of the project. To meet the goals of the project, artificial intelligence, computer vision, machine learning, location tracking, Bluetooth wireless communication, and many other complex technologies are needed. These domains each require some type of specific technology ranging from a few dollars to a few thousand dollars. VISION uses the least expensive technology that can still meet the needs of the project. Due to the project using cheaper technology, the accuracy, speed, and performance of the parts are somewhat limited. Careful consideration was used to ensure that the parts selected for this project will meet the requirements, while not being too expensive for a user to buy themselves.

4.2.2 Environmental Constraints

The VISION project is primarily going to be used indoors either in pool halls or different venues with billiards tables for visitors or in private residences for people who own their own pool table. Regardless of the location, one of the environmental constraints is to be weary of is the sound factor. Many systems in VISION rely on audio feedback to move the user around the pool table or to provide feedback via audio. Proper caution is taken to make sure that the sound level is not overbearing for any user or those near the pool table. It is important that the sound provided stays audible and clear with minimal noise, and does not overlap when different systems need to provide audio feedback or instructions. One way VISION limits these audio outputs is using only the speaker system and Swift application as audio sources so the user knows where to expect the sound from. This reduces distraction and focus from the central Jetson Nano controller that will be used to coordinate outputs. A visually impaired user would only have to focus on sound coming from the speakers at set locations and and feedback from the Swift application.

A lot of the system's components can also be repurposed for other needs depending on the user. The camera, localization aid, Jetson Nano and others can all be used modularly for other purposes offering the user additional options for reusing components if needed.

4.2.3 Social and Political Constraints

Billiards and social culture are inseparable in the societal domain. Constraints from this point of view should be examined as to allow for VISION to properly approach the social and political sphere. In terms of a physical social environment, an audio guidance oriented system may have limitations in its ability to be deployed. The proximity of audio output to the human ear can limit the efficacy of a guidance system significantly, and should be considered in both this prototype and in future design considerations thereafter.

The view of an assistive technology to the cultural and political masses primarily garners a positive view. Some cultural groups may look more highly on this system if they have a higher tendency or desire to play pool, and communities with impaired individuals will certainly find it a beneficial technological advancement. However, the guidance mechanism is skewed to benefit one group over the other by means of a selected language being prioritized, this can lead to an inability for said group to be able to gain the benefits of the design.

4.2.4 Ethical Constraints

The main ethical constraint would be ensuring that the user's privacy is respected especially if the VISION systems are being used in pool halls where any number of people would end up using the product. The camera system should not be used to record any user, player, or individual in the vicinity of the table. The camera system will be pointed above the table at all times and will be solely used to detect the balls still in game as needed for computer vision purposes.

Communication between the VISION team and the SCRATCH team for the dual project is done through a secure Bluetooth low energy connection, limiting interference and increasing privacy for a user.

4.2.5 Health and Safety Constraints

When new technologies seek to assist visually impaired individuals, the safety of the user is priority one. Creating a device that harms rather than helps a user is the worst case scenario, and must be considered to make sure a design is an additive to the lives seeking assistance. Constraints of VISION in this regard stem primarily from the navigational system in place. Navigating a table with limited awareness of surroundings can easily lead to a user tripping over scattered or loose items. In the case of VISION, the apparatus being used to hold up the camera is a constant obstacle that must be considered when navigating the user. The user guidance algorithm will never require a user to walk around, through, or over the camera stand to ensure the safety of a player. Although a player may have to walk further to take a shot, the safety of the player will be guaranteed and is one of VISION's top priorities.

In any project including electrical components, proper insulation and safety measures for all components must be considered to prevent the user from any chance of electrical shock. Additional electrical signals in audio that are used for output guidance should be in a form that is also safe for the user in both electrical contacts and auditory capacity. For instance, proper frequency, signal shapes, and volume were tested to ensure VISION prevents damage to hearing for users that rely on this ability.

4.2.6 Manufacturability Constraints

One of the biggest manufacturability constraints was the availability of the parts, especially the Jetson Nano. VISION ordered major components early to ensure they were available in a timely manner because they came from overseas. Many of the components used for the project also had similar backup products that could be used in place of the primary component if availability became an issue. Overall, VISION did not suffer from the unavailability of parts because the team ordered parts early in the process.

VISION was constrained by skill for encasing, wiring, and propping up different components. For instance, great thought was put into the camera stand to ensure its functionality, ease of set up, and ability to be transported. The table, speakers, beacons, and the camera system are moveable as a single system. Wiring from the speakers to the Jetson Nano was another concern, as it has to be flexible enough to not be an issue for someone moving around the table.

4.2.7 Sustainability Constraints

The system isdesigned for long-term use. The VISION system has a good mix of battery-powered devices and wired devices that both incorporate additional constraints in the system. The battery-powered devices such as the beacons have enough battery to last for a year while being constantly powered on. Other battery-powered components follow a similar or better lifetime cycle.

The Jetson Nano is susceptible to different issues as any computer would be. Careful consideration was taken to ensure that all the computationally intensive portions of the system running on the Jetson in parallel do not exceed the processing power of the Jetson.

Other systems that are powered via wiring from outlets also introduce constraints on power consumption for the user, as well as issues with heating where applicable. The total system takes precautions to ensure that no components overheat by using regulated power supplies with fuses where appropriate.

5. SYSTEM HARDWARE DESIGN

This section goes into the details on the hardware design of the entire integrated system. As the research section dove into the various components of the system and how they facilitate the goals of the design, this section discusses the specific components that realize those goals and the manner in which they interact with one another and are connected.

5.1 Billiard Table

From pool halls to at home setups, billiards tables come in a range of shapes and sizes. Determining a table that best meets the desired needs of the project is crucial to the mapping of the design. Considerations for this selection range from ease in mobility of the table, sturdiness, ability to facilitate all subsystems and adaptations, robustness to testing common occurrences, and ease of display for showcasing purposes.

The standard for billiards tables includes six pockets and is in a rectangular orientation with two pairs of matching sides at a 2:1 length ratio (Roeder). Tables come in four standard size orientations as followed (Vudrag):

- Standard - 8ft x 4 ft dimension. This size is commonly used by at home and beginner setups. It has enough space for complex shots, while not requiring too much power to practice basic shots.
- Large - 9 ft x 4.5 ft dimension. This size is the recommended professional orientation as it requires more physical skills to move balls to desired locations. Certain shots are more challenging with greater distances, such as when balls are in close proximity. Beginners have been shown to struggle on this type of table
- Bar Box - 7 ft x 3.5 ft dimensions. This orientation is preferred by some for its ease in ability to make shots, allowing it to be a popular orientation for social settings. Several common issues springing up from the use of this type of table include: tough to reach pockets, poorly matted felt, dead rails, and issues relating to cue ball size. Clustered groups become more common in this setting and create a more luck based game compared to skill focused playthrough.
- Miniature - This table orientation encompasses tables ranging in sizes of the longer length from 20 inches to six feet. These sizes are commonly used for tabletop billiards or by children. Rooms with limited space will possibly be a proper fit for an orientation such as this as well. These sizes are not expected for use in a serious game of pool.

In respect to VISION, the proof of concept aspect of our project and the augmented scale of the game that is planned to be deployed is best performed at smaller orientations of size. The scale of the table also positively correlates with price, so a smaller orientation table will best suit our endeavors. While the large orientation is quickly ruled out, bar box and standard orientations would be favored in the case of an at home asset for appearance. An additional benefit of these orientations are the opportunity to develop the project on a folding billiards table. This type of table would be accompanied by the asset of mobility to easily transport it within a team member's car for presentations and development of the prototype project.

Several suppliers can facilitate a table as specified at a range of prices and specifications. Two tables of interest meet the criteria of lower size and foldability from the suppliers of Blue Wave and Rack as shown in figure 5.1. These are comparable models, with the Blue Wave model being of higher quality, dexterity, and price to the half-priced Rack model.

The Fairmount model was chosen for the final design. Initially, the Rack model was going to be used, but upon realizing the smaller size constraints included smaller balls and a noticeably detrimental impact to game performance, the larger table was chosen for use in VISION.

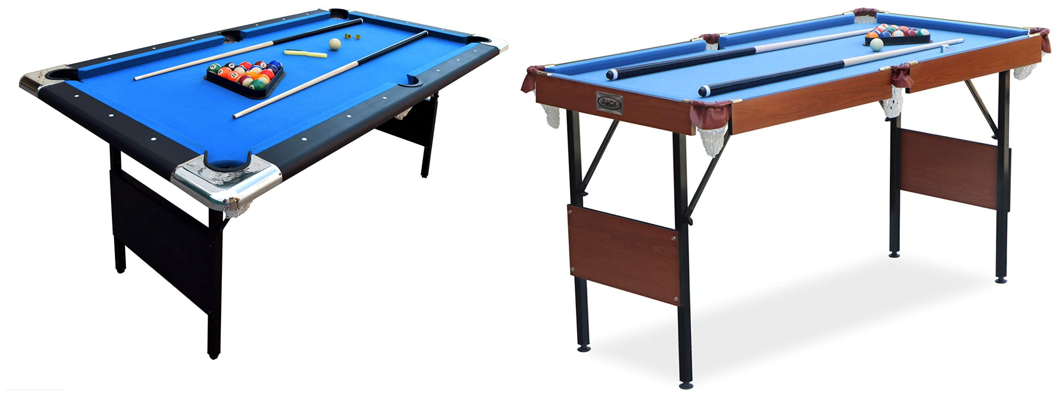


Figure 5.1: Blue Wave's Fairmount Table (Left) & Rack's Crux 55 Table (Right)

5.2 Processor Selection

The Jetson Nano 4GB Development Kit is the desired processor for this project. The Nano is a high-performance embedded computer equipped with a powerful GPU that can be used for machine learning, artificial intelligence, computer vision, and other computationally complex tasks. The Jetson Nano is more than capable of performing all of the benchmark machine learning frameworks. The Raspberry Pi and Coral Dev boards could perform some of the benchmark tests, but there were many tests that the boards could not support. The Nano's ability to support a variety of machine learning tasks is what makes the board so desirable.

There are benchmarks where the Coral Dev board does outperform the Jetson Nano. However, the large number of benchmarks that the Coral Dev board could not complete is worrisome. The Coral Dev board was purpose-built for TensorFlow Lite and it appears that not even the standard TensorFlow framework can always be implemented on the board. VISION does not intend to use TensorFlow Lite, so it would be risky trying to use the Coral Dev board to run software that it was not designed for. Although the benchmark tasks were mainly related to real-time video processing, the results display how versatile of a device the Nano is.

Compared to the other boards, the Jetson Nano does lack Wi-Fi and Bluetooth capability. Although an ethernet connection can be used in place of Wi-Fi, there is a large portion of the project that relies upon Bluetooth for communication. There are numerous adapters available on the market that can be added to the Nano to provide both Wi-Fi and Bluetooth connectivity. The Edimax N150 adapter is a 2-in-1 Wi-Fi and Bluetooth 4.0 adapter that plugs directly into one of the Nano's USB ports. This adaptor is relatively inexpensive and significantly increases the usability of the Nano.

Furthermore, the available port selection on the Jetson Nano is more than sufficient to support all of the peripheral devices needed by VISION. The Jetson Nano has a USB-C 3.0 port , a USB-C 2.0 port , two USB 2.0 ports , a USB 3.0 port , HDMI port, ethernet port, and 40 GPIO pins. With the addition of the Wi-Fi and Bluetooth 4.0 adaptor, the Jetson Nano will also have two forms of wireless connectivity.

To ensure that the Jetson Nano can support all of the peripheral devices needed, figure 5.2 shows the tentative connection diagram for the Jetson Nano. The Jetson Nano is the central processing unit for VISION and will coordinate communication with all of the other devices.

A significant amount of communication will be done using wired connections. The USB-C 3.0 port will be used to power the Jetson Nano from a wall power outlet. The USB 3.0 port will be used to communicate with the web camera for the computer vision system. The Nano will use a USB 3.0 port to interface with the computer vision camera. The Nano will communicate with the Swift application and the SCRATCH team through two distinct MQTT connections. The Nano will communicate with the ESP32 located on the PCB through a BLE connection.

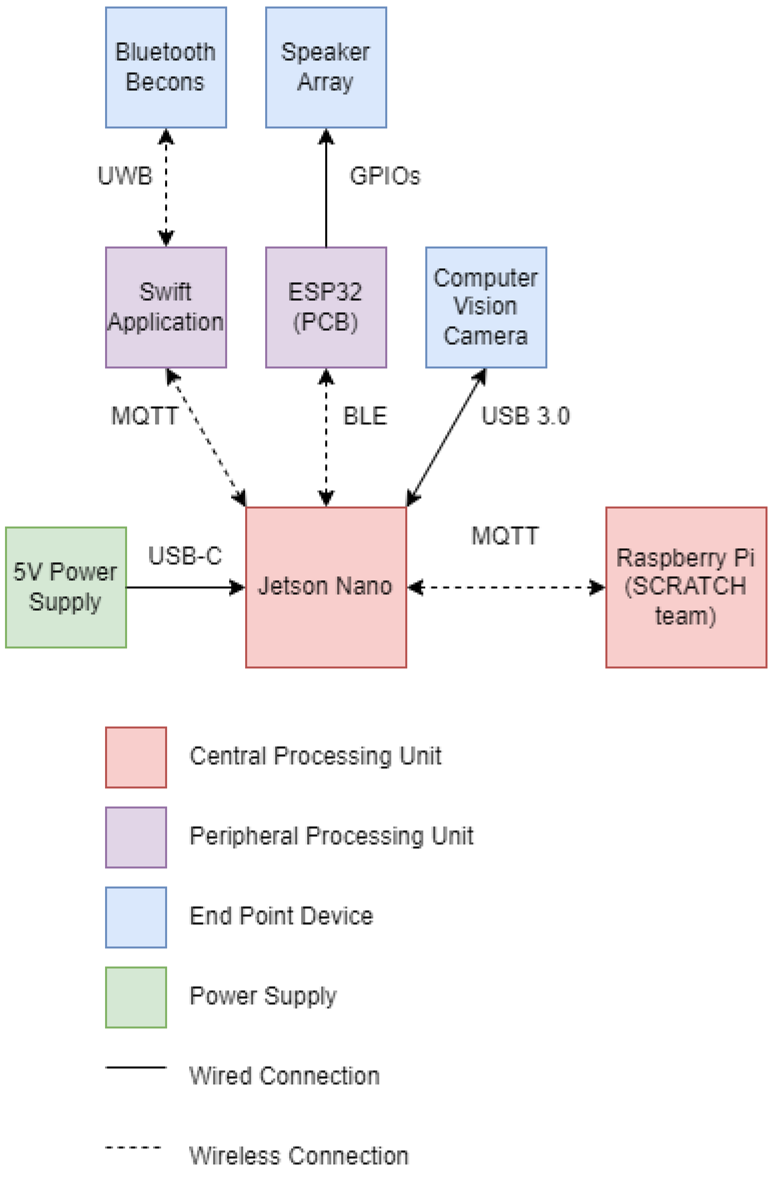


Figure 5.2 Jetson Nano Device Connections

5.3 Camera

5.3.1 Computer Vision Camera

The computer vision section of this project is responsible for obtaining an image of the current state of the billiard table and determining the location of all the billiard balls in play. The computer vision algorithms rely on a high-quality image of the table state to be able to process the image and extract the necessary information. The camera is mounted above the table, takes clear pictures of the table in a variety of lighting conditions, has a wide field of view, and is compatible with the Jetson Nano.

The camera will take pictures of the billiard table that will be processed by computer vision algorithms. Higher quality images will provide better contrast between the background and the billiard balls of interest. To ensure the best results, a camera that provides a video resolution of at least 2 megapixels is desired. If a lower resolution is needed by the image processing software, it is possible to reduce the resolution to what is needed. However, it is not possible to exceed the maximum resolution of the camera. For this reason, the safest option is to get a high-resolution camera and scale down the resolution if needed.

The field of view of a camera describes how wide of an angle a camera can view. A field of view corresponding to 60° would only see a small portion of what is in front of the camera while a field of view of 180° would see everything that is in front of a camera. A larger field of view allows for the camera to be positioned closer to the billiards table. Most webcams have a field of view of 60° - 90°. The ideal field of view for this project is around 90°. A field of view of 90° will allow for the camera to be mounted about a meter above the billiard table and still be able to capture the entire table (Pinke).

The Jetson Nano supports a wide range of camera interfaces including MIPI CSI, Ethernet, FPD-Link III, GigE, GMSL, PoE GigE, USB, and V-by-One HS. Of these interfaces, Nvidia recommends using a MIPI CSI or USB interface because these options are supported natively (NVIDIA Corporation "Taking your first . . ."). Additionally, both of these camera types can provide high-resolution images at an affordable price.

Summary of Requirements:

- Camera can be mounted above the billiards table
- Have a minimum video resolution of 2 megapixels
- Provide a field of view of approximately 90°
- Utilize an interface supported by the Jetson Nano
- Does not exceed $100 in price

MIPI CSI Cameras: MIPI is an alliance of large technology companies that develop specifications for devices in the mobile-computing industries. One specification defined in the MIPI standards is the CSI-2 (Camera Serial Interface - 2) which has quickly become one of the most popular interfaces for implementing cameras in embedded designs. CSI-2 is a high-speed protocol for sending images and video from a camera to a computer via a proprietary MIPI CSI connector.

In recent years, CSI-2 cameras have become the clear choice for many embedded processing applications. With the creation and wide-scale adoption of the CSI-2 protocol, many large electronics manufacturers have started manufacturing CSI-2 cameras leading to a wide variety of options in the market. For this reason, these cameras are relatively affordable and there are many options available for $20-$30. Furthermore, CSI-2 cameras provide higher bandwidth for pictures and images at a price comparable to USB cameras of much lower quality.

One of the most commonly used CSI-2 cameras for embedded applications is the Raspberry Pi Camera Module V2 which offers an image resolution of 8 megapixels and full HD video at only $25 (Raspberry Pi). The high performance at low cost is what makes CSI-2 cameras so popular. The main concern with the Raspberry Pi camera, and CSI-2 cameras in general, is the short cable length of the camera connector. CSI-2 cameras typically have a maximum cable length of 20-30 cm.

The short-range of CSI camera cables means that the Jetson Nano will have to be located next to the camera. Having the Jetson Nano next to the camera may not be possible based on the mounting location of the camera. The camera needs to be mounted above the billiards table facing downwards so that an image of the current state of the billiard balls can be captured. Having the Jetson Nano mounted above the billiards table would not be ideal because all of the other project components would have to have interface with the Nano in a hard-to-access location. Due to the limited length of connections for CSI cameras, it is unlikely that one can be used for this project.

USB Cameras: The next best alternative is to use a USB camera. USB cameras are natively supported by Jetson Nanos and are one of the camera interfaces recommended by Nvidia. Although the performance of USB cameras is not as high as a CSI camera, most USB cameras are suitable for the project requirements. Using a USB webcam will not require the Nano to be mounted directly next to the camera, allowing for the processor to be located in a more centralized location.

Many USB cameras will meet the requirements. It was determined that a moderately priced webcam would meet all of the requirements and nearly all webcams are USB devices. Many different webcams from reputable suppliers were considered. Four selected webcams that best meet the required specifications are summarized below. Any webcams that are not readily available for purchase or greatly exceed the budget requirements were not considered. Table 5.1 summarizes the specifications of the highest recommended web cameras within VISION's budget.

Camera	Manufacturer	Price	Resolution	Field of View
PowerConf C200	Anker	$69.99	2K	68° - 95°
PowerConf C300	Anker	$129.99	1080p HD	78° - 115°
C920s Pro Full HD Webcam	Logitech	$69.99	1080p HD	78°
C930s Pro HD Webcam	Logitech	$129.99	1080p HD	90°

Table 5.1 Summary of Camera Options

From table 5.1, the Anker PowerConf C200 is the best choice for the computer vision camera. This webcam is one of the cheapest cameras that not only meets but exceeds the project requirements. The camera has a video resolution of 2K, which is better than the 1080p resolution that the other cameras have. The camera also has three configurable field of view angles: 65°, 78°, and 95°. The ability to use different field of view angles will be helpful when testing the design to find a camera height and angle that allow for the clearest pictures to be taken. The PowerConf C200 also supports autofocus and low-light environments to capture the best possible image regardless of the conditions around the billiards table.

5.3.2 Computer Vision Camera Mounting

To capture an image of the billiard balls, a camera will be needed above the billiards table. The camera can either be fixed to the ceiling of the room where the billiards table is located or mounted to a structure that extends over the billiards table. Ease of access, portability, and reliability should all be considered when selecting how to mount the camera above the billiards table.

Ceiling Mounted: Having the camera mounted to the ceiling of the room is appealing because there would be no obstructions to the billiards table. This is ideal because players would not have to maneuver around a structure and possibly have to alter shots due to the camera stand being in the way. However, this implementation would not allow for the billiards table to be easily moved between locations and limit where the system can be implemented. Furthermore, if the camera is mounted at different distances above the table, the computer vision algorithms being used may need to be revised to account for the changes in distance.

Fixture Mounted: Another possible way to mount the camera is to create a semi-permanent fixture that extends above the billiards table. Such a fixture would allow for the camera to be mounted above the table regardless of the table's location and an example is shown in figure 5.3. This solution would also allow for the entire system to be transported between locations without having to mount a camera on a different ceilings.

This approach will also make the computer vision algorithms more reliable because the distance from the camera to the billiards table will be fixed regardless of where the system is being used (Pinke).

Using a fixture to mount the camera above the billiards table seems like the better solution because the billiards table will need to be mobile to some extent. As of now, the billiards table does not have a permanent location. Being able to move the table without having to recalibrate the camera, modify the computer vision algorithms, and remount the camera to a ceiling are all important factors for developing the system. The structure will only need to support a small webcam and can be made small in comparison to the table size. When the camera structure is made, priority will be given to minimizing the structure size to have as small of an impact on the billiards table as possible.

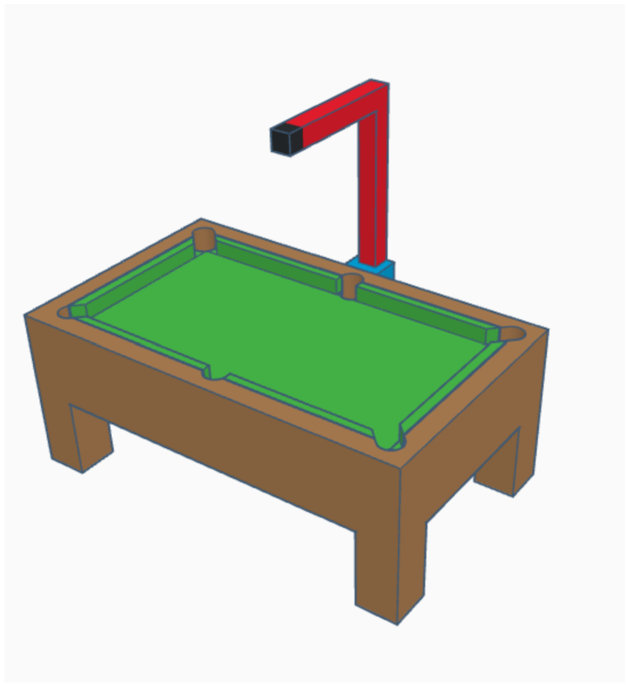


Figure 5.3: Example of Fixture Mounted Camera

5.4 Localization System

Based on the different options presented in the research section, VISION has decided to focus on UltraWide Band as the localization scheme and navigation scheme. The system will navigate the user around the pool table, from their initial position to the target position for optimal shot computed by the pool game algorithm along a path determined by VISION's navigation algorithm. In essence, VISION will compute the user's localization at every point using trilateration. When the system gets input from the user that they are ready to make their next shot, a series of actions begin to allow VISION to determine where the user is around the table at the current time.

Esimote UWB Beacons: Three beacons are placed on the pool table at specifically chosen locations. The beacons send out advertisement packets at the smallest possible interval in order to get the best accuracy. The beacon mounting locations are shown in figure 5.4 for a regular pool table of length 2.54m horizontally and height 1.27m. Figure 5.5 displays the Estimote beacons used for VISION

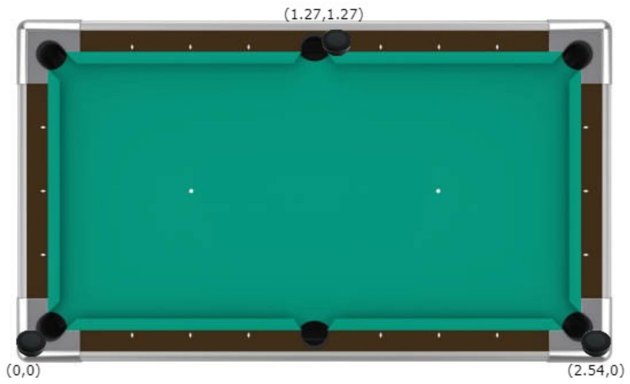
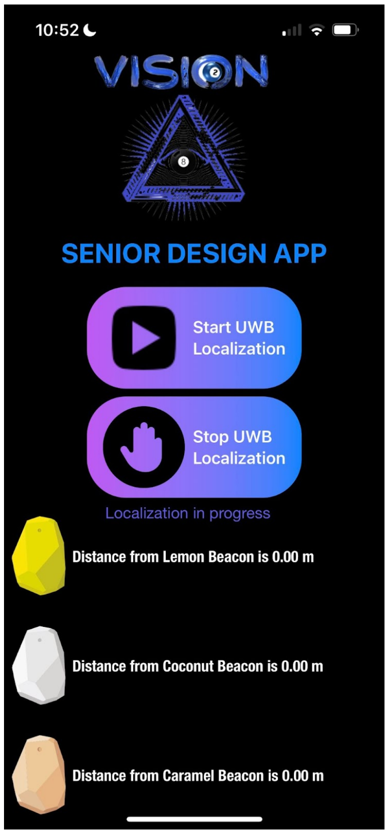


Figure 5.4 Beacon Location on Billiards Table

Figure 5.5: Estimote UWB Beacons

The choice of beacons are the Ultra Wide-Band beacons from the company Estimote. A few reasons for this decision include an already available SDK from the company which advertises that the beacons can communicate with iphone's U1 chips providing distance between the beacons and the iPhone within centimeters of precision which is perfect for the current applicable. They also offer a two-year long battery life, and inertial sensors to account for movable objects. Estimote offers the beacons in three packs which are shown in above figure 5.5. The three beacons can be differentiated based on their colors: coconut, lemon, and caramel. The beacons are used by the user localization system to track the user around the table. An app was designed for the users's iPhone that is used as the primary reader between the beacons and the visually impaired individual.

Swift App: A Swift app was designed for the user's iPhone. Swift is chosen as a language because the SDK provided by Estimote is written in Swift. A key concerns of the application is designing an app with visually impaired individuals in mind. For instance, the app remains simple and only have one interfacable region as shown in figure 5.6. Compared to most modern apps with numerous pages, VISION keeos its app simplified to be used without having to worry about where specifically within the app the user is going to be. The app also provides both tactile and audio feedback to the user, which allow them to know what has been pressed on the app. Hence, VISION aimed to only have two touchable regions (buttons) on the applications interface, one to start or resume localization, and the other to pause localization. Both of the buttons provide vibration and audio feedback when touched so the user knows exactly what is happening when they interact with the screen. In addition to the basic audio feedback, the application implements audio feedback for the guidance system and localization system. Some of these vocal feedback options include letting the user know when the game is over, when he/she hit one of his/her own balls or the opponent balls, letting him/her know when to move towards the speaker, or rotate towards the closest speaker for increased accuracy. The app then communicates with the Jetson through MQTT (Message Queuing Telemetry Transport) providing the readings of the distance to each individual beacon.



Localization in progress

Distance from Lemon Beacon is 0.00 m

Distance from Coconut Beacon is 0.00 m

Distance from Caramel Beacon is 0.00 m

Figure 5.6: VISION User Localization Application

Jetson Nano: The Jetson Nano receives the distance values from the app. A Python script runs on the Jetson Nano to compute the x and y coordinates, through trilateration, of the user with respect to system origin. The (x,y) position is smoothed and filtered for accuracy and converted into speaker readings such that VISION knows which two speakers are closest to the user's current position. This speakers' readings are then sent to the user guidance system.

5.5 User Guidance System

At the heart of VISION's goal is the ability to guide an impaired user to a desired location on the table and allot them the opportunity to make desired shots. The method for achieving this guidance must have solid logistics, be reliable within worst case board states, and be safe for the user's traversal of the table. The following outlines the methodology to accomplish this and the specifics of the design that minimize unwanted circumstances within gameplay.

5.5.1 Audio Array Design

The two primary methods discussed in the technology review conducted in section 3.2.5 on guidance relied on audio and haptic feedback. Haptic feedback is revealed to be a great technology in tandem with other devices to create a detailed picture for users in dynamically changing environments. However, for the static pacing of VISION that includes a necessity for directions around a stationary table and angular orientation relative to it, the limited information delivery that can be done by haptic feedback is a hindrance. Moreover, an apparatus on the user would be required for the navigation around the table, which would add more complexity to both the easy use of the system and the SCRATCH team's present user system. This system also would have flaws in communicating coherent instructional guidance and would require a feedback loop for validation of positioning of the user.

On the other hand, audio guidance can be deployed in a rather convenient manner that comes with several advantages. With the use of several small speakers around the table edges in an array fashion, guidance algorithms can pinpoint the desired path for the user to take around the table for a designated shot. This can be accomplished with an updating location of the user being referenced for the proper speakers to activate, giving an accurate route for the user's destination. Once in position, the array can then be turned into a angular guidance system to orient the user within a margin of error of the ball to then hand off to the user team for finer user mechanics.

To properly distribute the necessary signals to a single desired speaker at a time, the Jetson Nano will be handle the primary algorithm that will communicate signals via BLE to an ESP32 (located on the PCB). This ESP will interpret the data on speaker activation and then select the proper speakers to be activated by use of a demultiplexer that is able to select a singular output via digital selection pins. To access upper levels of volume, the output signal will be integrated with an audio amplifier from the ESP. A prototyped singular speaker design is shown in Figure 5.7, showing an example of how an ESP32 can communicate the described outputs. Navigation algorithms described in Section 6.3 explain how the Jetson will comprehend speaker choices. Once the ideal position and orientation are reached, signals weill be sent to the ESP to stop the speakers until further navigation is desired. The output signal will consist of a fluctuating PWM square wave with a 50% duty cycle that turns on and off every half second. This allows the user for easier location and orientation based on the speaker outputs.

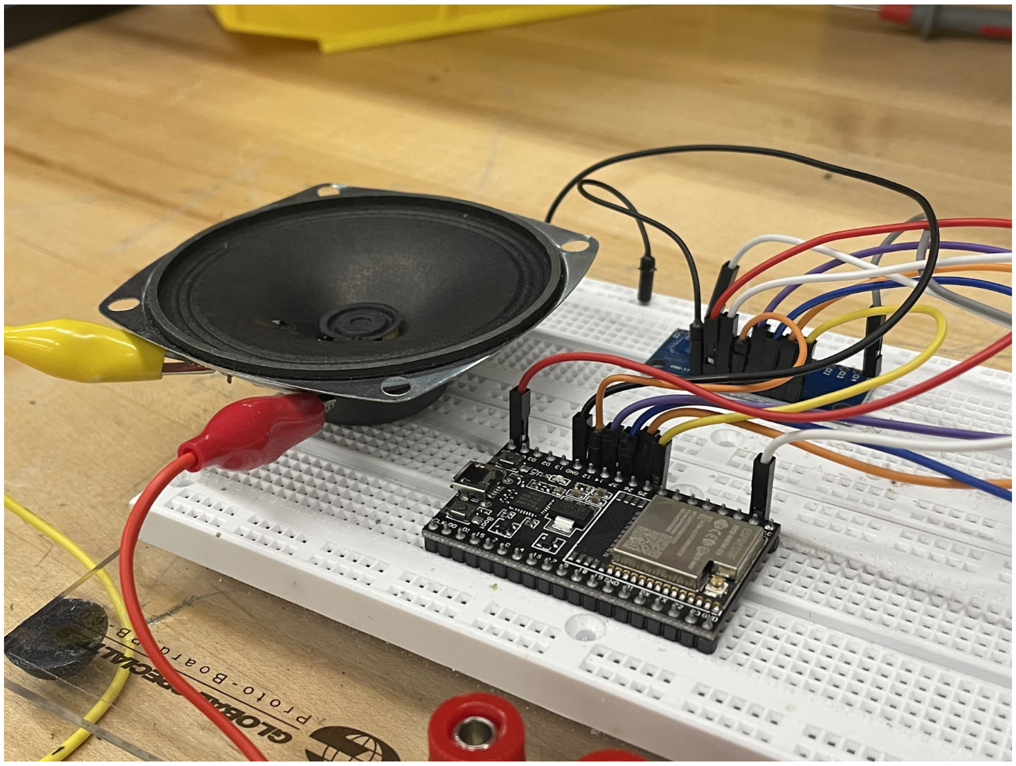


Figure 5.7: Prototype Speaker Activation Design

The specified positioning for the speaker array in VISION will include 12 speakers at the perimeter of the table as shown in Figure 5.8. This method allows for the positioning guidance goals of VISION to easily be attained, and gets the orientation parameters within an acceptable margin of error as described in Section 5.5.4. Each speaker is approximately 19 inches apart.

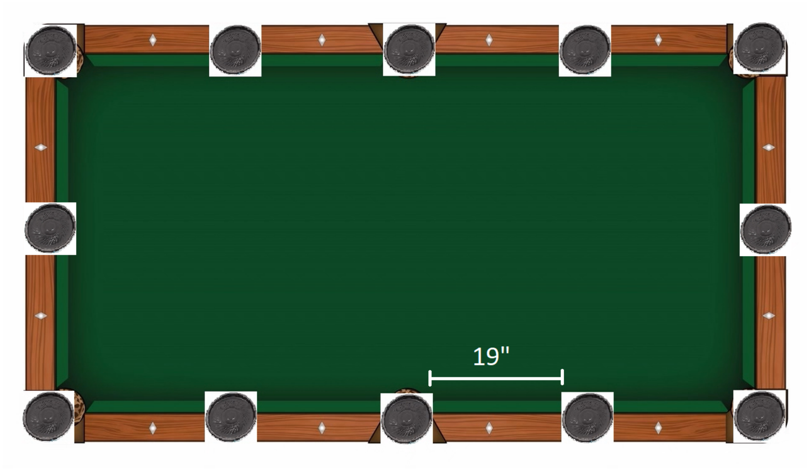


Figure 5.8: Designed Speaker Array

5.5.2 Positioning Method

Navigation of the impaired user will rely primarily on audio guidance from VISION's table speaker array. In the case of positioning, corner speakers will be activated to best guide the user along a 2D plane that consists of only two possible directions to the user. In any instance of user location, a speaker on the corner of the table will be activated with the user having knowledge to walk in the direction of the origin point of the sound. Upon reaching the desired location, the speaker will cease to output sound or will output from an alternative location if in an improper location. The speakers will direct the user in both directions as shown in figure 5.9.

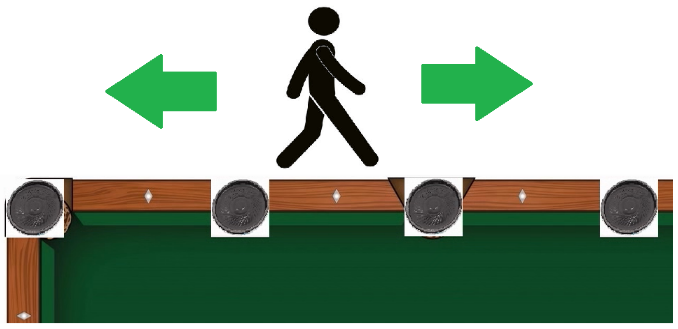


Figure 5.9: Bidirectional Guidance Possibilities

5.5.3 Orientation Method

Upon the user reaching the desired location around the table, the speakers are used to orient the user to an approximate location that places them in line with the cue ball and ultimately the direction in which to shoot. Since the orientation mechanism lacks an active feedback method, the orientation speaker will play for a 10 second period to give the user ample time to shift position.

This mechanism being the case does leave a possibility for a variable margin of error for the user. The calculated worst case angular margin lies at 7.1° with a maximum possible arc difference of 8 inches. These values are within the 15° worst case scenario proposed in VISION's project requirements, and allows for a viable hand off to the SCRATCH project for fine tuned movements. Figure 5.10 further shows the worst case margin of error scenario. Additionally, locational accuracy may also introduce added margin of error that must be smoothed out for most cases and troubleshooted for higher accuracy to give a possible starting point to the SCRATCH design.

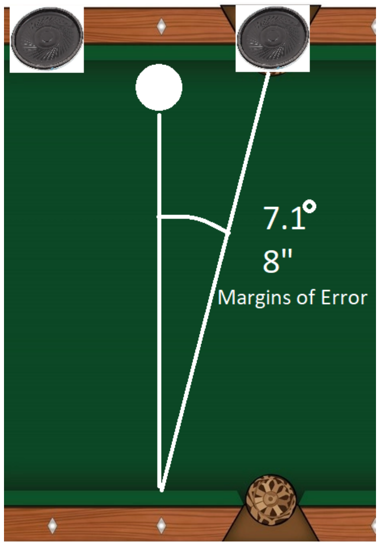


Figure 5.10: Worst Case Margin of Error Estimation

5.6 User Control Interface

To properly control the full array of VISION's functionalities, a custom user interface was designed to relay critical commands to the system. The section on user commands outlined three possible command interfaces for the design, including a remote control on the user, centralized control on the table for an assistant, and an audio command interface. As this project is a proof of concept, the simplest command interface will be integrated in a centralized command interface for an assistant to perform necessary commands. The interface will be minimally invasive to the action within gameplay, and will largely be for a short list of commands that are integral to procedural operations of VISION.

There will be four push buttons that will be integrated on the PCB of the project. These will include commands for starting, pausing, and stopping game play as well as recalculating a shot. The first three commands are integral for the usability and ease there of for the player, and the latter is important for allowing the system to recompute a shot if the assistant belives there has been a mistake.

5.7 Communication Network

The communication network for the hardware will allow the different computing systems to handoff information and control with the correct timing. Ensuring the purchased hardware is compatible with the protocol discussed below is another key factor in making sure there is a successful communication network.

5.7.1 Communicating Systems

The following subsystems must be connected for our system to work properly:

- Computer Vision
- Shot Selection
- Table Feedback
- User Localization
- User Guidance
- User Control Interface
- User Team System

Some of these systems will be present on the same hardware, while others will require some form of communication protocol to receive necessary information. The computer vision and shot selection algorithm will be on the Jetson Nano. This will leave the communication between these systems as a software design specification. User guidance will use a microcontroller that requires input from the Jetson Nano. The Jetson Nano will communicate with the microcontroller using BLE. The user localization system needs several pieces of hardware to function properly. It needs the beacons, the scanner user's iPhone, and the Jetson Nano for calculation. The Jetson Nano will connect to the Swift application via MQTT. The Swift application will connect to the beacons with Bluetooth. The user control interface will require two pieces of hardware, the transmitter and the receiver. The control interface will connect with the Jetson Nano via BLE. The Jetson Nano will act as a client and the control interface will act as a server. The user team will receive all needed information through one BLE communication line connected to the Jetson Nano. This will reduce the coupling of the systems, which is generally best practice. The Jetson Nano will act as a server while the user team's processor will act as a client.

5.7.2 Communication Protocols

Event vs State Driven Communication: It can be hard to define the VISION network into event or state driven as described in (Rollins). While there is an event driven process controlled by the user control interface, this is a one time action which places the system into a state, such as paused or in play. VISION has decided to treat the system as an event based system, this is because it will go dormant without user interaction.

Processor Communication Capabilities:
Table 5.3 summarizes some of the relevant processors and what types of communication protocols they have access to.

Processor	**I2C**	**UART**	**SPI**	**Bluetooth**	**Wi-Fi**	**Ethernet**
Jetson Nano	4	3	2	Yes*	Yes*	Yes
MSP-EXP430FR6989	2	2	4	No	No	No
ESP32	2	3	3	Yes	Yes	Yes

Table 5.3: Comparison of Communication Interfaces

*Note: the Jetson Nano does not have Wi-Fi or Bluetooth connectivity by default, but can gain access to these forms of wireless connection with an adapter.

From the chart it can be seen that there are many available wired connections for communicating between the Jetson Nano and the MSP-EXP430FR6989. However, there is an issue with the Jetson Nano communicating with the ESP32 over a wireless connection. With the standard Jetson Nano there are a couple of options we could take for wireless communication.

- Connecting the Jetson Nano to ethernet and the ESP32 to WiFi. The two could then make API calls over the internet
- Setting a second proxy ESP32 in a wired configuration to the Jetson Nano, then communicating through bluetooth or WiFi with one ESP32 to the other.

These two options are possible but would be more complicated than getting a Wi-Fi or Bluetooth adapter for the Jetson Nano that would allow for direct communication. An example would be the Intel Dual Band Wireless-Ac 8265 w/Bluetooth 8265.NGWMG along with an antenna that can support both 2.4 and 5Ghz. The suggested antenna from a tutorial suggests using a molex film antenna which costs approximately three dollars. There are additional kits which come with the antenna and card already connected for similar prices. VISION intends to equip the Jetson Nano with a Wi-FI and Bluetooth adapter.

6. SYSTEM SOFTWARE DESIGN

6.1 Computer Vision System Software Design

The system must be able to identify the billiard balls in an image and determine their color and location. Section 3.2.2 outlines some of the relevant computer vision algorithms, available in OpenCV, that can be utilized to reach the computer vision goals. This section describes how the computer vision system will be designed and what algorithms will be used.

Before discussing the specific algorithms chosen, it is important to discuss the inputs and outputs of the computer vision system and how the system will interface with the rest of the project. The initial input to the computer vision system, and the entire project, is an image of the current state of the billiards table. This image is processed through a variety of algorithms and will output a (Python) list containing elements and their relative locations. This list is then used by the shot selection system to determine the best shot to take. The elements in the output list of the computer vision system will contain the relative location of the billiard balls and a string to differentiate between the billiard ball colors.

The input image for the computer vision system is run through multiple separate algorithms to extract different information from the image. It is important to maintain the input image so that the same input can be used for all of the algorithms. For all algorithms that modify an image, a copy of the original input is supplied rather than the original image.

The locations in the list need to be relative locations rather than absolute locations. Relative locations refer to the distance, in pixels, from a defined reference point for a selected feature of interest. Absolute locations refer to the raw pixel location in the input image. Due to the input image including some of the unwanted background, all of the pixel locations that are found are localized to a point of reference. The selected point of reference is the top left corner of the playable area of the billiards table. This reference point is used to stay consistent with the coordinate system used by OpenCV and will also represent the location of the top left pocket on the table.

For all of the billiard balls found by the computer vision algorithms, their relative locations need to be included in the output list. Additionally, a string will also need to be included with each billiard ball entry to specify if the billiard ball is the cue ball, the black ball, a blue ball, or a green ball.

Billiard Table Isolation: The billiard table isolation portion of the computer vision system refers to being able to extract the playable area of the table from the input image. For this project, the playable area refers to the region of the billiards table where the billiard balls can be. This region is the nearly rectangular region of the table that is recessed from the borders of the table. Isolation is needed to localize the billiard balls to a reference point, verify that the contours found in the image are in the playable region, and determine the location of the pockets.

To isolate the playable region, a series of image manipulations are applied to the input image to extract. The camera stand will be located in the same position relative to the table anytime VISION is used, so a static approach to isolating the background can be used. VISION extracts the image vectors representing to the image pixels and removes the unnecessary pixels by using vector manipulations found in OpenCV.

To localize the billiard balls in the image, a reference point needs to be chosen to localize the balls to. The upper left corner of the contour found by manipulating the image is used as the reference point. As mentioned previously, this reference point is chosen to align with the coordinate system used by OpenCV. To localize the billiard ball coordinates to this point, simple arithmetic is needed.

The reference point, p, will have some positive, non-zero coordinates (x_0 , y_0). The reference point coordinates must be non-zero because the reference point will not be the upper left corner of the input image. If the reference point is assumed to be the new origin and denoted p^* with coordinates $(0 , 0)$. All of the billiard balls can be localized to the reference point p^* by subtracting (x_0 , y_0) from their coordinates. This transformation will ensure that all billiard ball locations are positive, non-zero values because no billiard balls can be above or to the left of the reference point. This claim can be made because any region above or to the left of the reference point is not in the playable region of the billiards table.

The localization of the billiard balls to a reference point can easily be reversed by adding the offset values, (x_0 , y_0), back to every localized billiard ball location. The reversal of the coordinate system back to the true pixel values will be useful if any features need to be shown on the input image. For lines to be drawn properly, the true pixel values, rather than the localized values, of the billiard balls need to be used. The localized values on the input image should only be used by the shot selection algorithm. To ensure that the original coordinates can be recovered, the offset values are be stored for the duration of the program execution.

Once the playable region has been discovered, it will be possible to determine if the contours discovered in later portions of the image processing are in the playable region. The borders of the rectangular contour will have a minimum and maximum x-coordinate and y-coordinate. These minimum and maximum values can be used to ensure that any contour discovered in the image lies within the playable region of the table. If any object is discovered outside of the minimum and maximum coordinates, it can be discarded.

The rectangular contour outlining the playable region of the table can also be used to find the locations of all of the six pockets. Once the coordinates have all been localized, the upper left pocket is at $(0 , 0)$, the upper right pocket is at $(x_{max} , 0)$, the lower left pocket is at $(0 , y_{max})$ and the lower right pocket is at (x_{max} , y_{max}). The middle pockets can be computed by finding the midpoint between the two adjacent pockets. The top middle pocket is located at $(\frac{1}{2}x_{max}\ ,\ 0)$ and the bottom middle pocket is located at $(\frac{1}{2}x_{max}\ ,\ y_{max})$. Defining the pocket conventions this way means that the locations of the pockets only depend on the four corner values of the rectangular contour found with image manipulation.

Finding the Billiard Balls: To find all of the billiard balls in the input image, the Hough Circle Transform will be used. This algorithm is used because it is specifically tailored toward finding all of the circles in an image. The algorithm allows for the parameters to be modified as needed to only detect circles of a certain radius. This characteristic is useful because all of the billiard balls are of the same size. The expected radius of the billiard balls was determined experimentally so the algorithm can enforce size restrictions on the circles found to ensure that only billiard balls are discovered.

Additionally, this algorithm was chosen for its ability to detect touching circles and partial edges of circles. The algorithm traverses the discovered edges in an image and looks for points of intersection, and assigns points to these values. For this reason, two touching billiard balls can still form two distinct radii which enables the algorithm to detect both billiard balls. This trait of the algorithm is especially appealing because other algorithms are sensitive to objects being too close together. This algorithm is also able to detect circles from partial edges. Even if there is only a portion of a circular edge present, this algorithm is still able to traverse the edge and identify that the edge represents a circular contour. This behavior of the algorithm is ideal for situations when the lighting is not optimal and there are shadows or unclear edges in the input image. The robustness of this algorithm is another reason why it was selected for this project.

Initially, the Hough Circle Transform was run on the image so that it returned a list of discovered circles. Initially, there were no restrictions on the radius of circles returned so that the expected radius of the billiard balls could be determined. This testing occurred in various lighting conditions and with various numbers of balls on the table. A reliable minimum and maximum radius were discovered and these parameters were implemented into the algorithm. Including the minimum and maximum radius allows for the algorithm to automatically exclude any contour that is too big or too small.

The list of all discovered circles is iterated over and all of the coordinates are localized to the reference point. The locations of the contours are checked for being in the playable region. If the coordinates of the contour fall within the playable region, the location is added to the output list. If the coordinates of the contour are not in the playable region, that contour is ignored. The output of this part of the computer vision system is the output list with all of the discovered billiard balls and their localized locations appended.

Detecting the Ball Colors: The ideal way to detect ball colors is to make a small addition to the previous section. The previous section outlines how to find and filter all of the circular contours in an image using the Hough Circle Transform. An additional step can be added to this process to determine the color of the ball. Although the transform requires a binary image as input, the locations of the contours that are found can also be applied to a color version of the same input. This allows the color of the discovered contours to be checked before adding these locations to the output list.

The RGB values of the discovered contours can be compared with predefined threshold values. A perfectly white RGB pixel will have the values of [255, 255, 255] for the red, green, and blue color channels, and a perfectly black RGB pixel will have the values of [0,0,0]. A lower bound was experimentally determined such that the white ball, black ball, green balls, and blue balls can be differentiated. It was important to determine threshold values that do not provide any false positives when iterating through the contours. This color check is implemented before a billiard ball's location is added to list. The possible labels for billiard balls are *white_ball, black_ball, blue_ball,* or *green_ball.*

6.2 Pool AI

Extensive research for the shot selection algorithm has been completed in section 3.2.1. With many possible implementations to choose from it is important to first clarify the system requirements.

- Input: List of current table state, this is the (x,y) location of every ball, along with the classification of every ball.
- Output: The force and angle to hit the cue ball

Summary of Requirements:
- Algorithm produces output in under 25 seconds
- Algorithm produces shots in which the end of a 3 to 4 foot pool cue will not intersect with the dimensions of the table
- Ensure that 1 foot from the cue to the shot angle does not intersect with any balls

The algorithm must be quick enough as to not impede the game flow. If an algorithm takes more than 25 seconds, VISION will cut down on its accuracy and how many moves ahead it is planning. The user will likely not be hitting every ball in, so branching into the future too far is not an efficient use of computational power. The algorithm must also make the correct decision in a very simple situation, prioritizing simple shot suggestions over more complex shots, even if advantageous.

Using an existing shot selection algorithm out of the box is currently not an option. Many are slow and connected to GUIs. They also lack the constraints of a real table, and will suggest shots which are not physically possible.

<u>*Timing Considerations:*</u> The existing shot selection algorithms will be stripped of their GUI for production mode, increasing performance. The search and heuristic based algorithms have built in physics engines which are required, these cannot be offloaded and decrease performance. The branching factors of the algorithms can be diminished to a smaller amount. While the algorithms are built to win on a single turn, VISION does

not expect nor need this level of accuracy. Reducing branching will dramatically speed up performance.

Realistic space considerations: The algorithm must give the player a shot which is reachable. For example, consider the shot shown in the top of figure 6.1. Even though this would be the best shot, there is no way the player could reach this. The better shot alternative would be something such as this the shot shown in the bottom of figure 6.1.

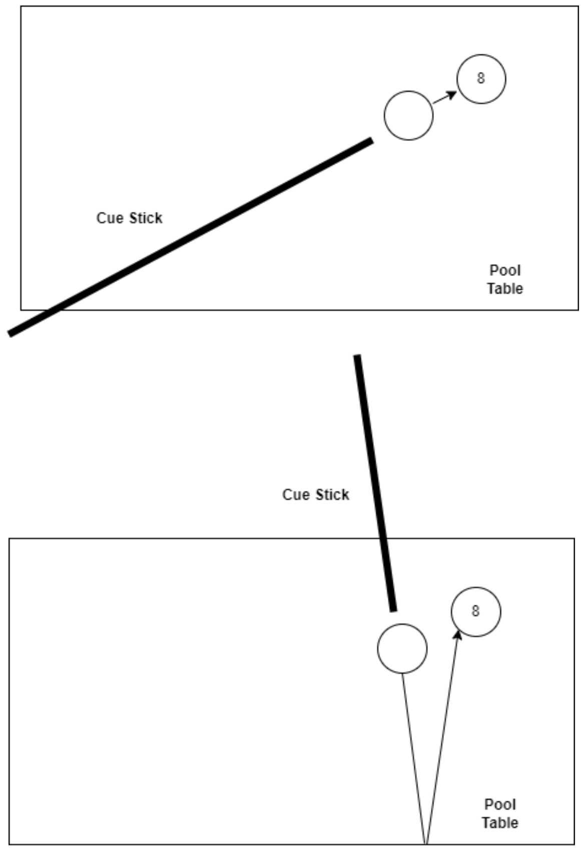


Figure 6.1: Example of Reachable Shot Issue

The main design problem was designing the algorithm so that it only considers realistic shots. An additional algorithm was made to ensure that the length the pool cue from the pool table wall is not too far for a user. User testing was conducted to determine the length in question. The algorithm was designed to follow these general steps. The algorithm also takes into account the width of the user's body. On one side of the table, the user's body will be in the way, on the other side, the user will have much more mobility.

Algorithmic Process: Below is the outline of VISION's algorithm with relevant parameters defined.

Max Extension= maximum distance the cue stick can be over the table
Current Extension = total distance the stick is over the table
User Width = the average space the user takes up
Shot Angle = angle the cue stick will hit the cue ball at
Cue Ball Coordinates = the center of the cue ball given in x,y
Cue Ball Radius = the radius of the cue ball
X Min = This is the left side of the pool table and represented by 0
Y Min = This is the top of the pool table and represented by 0
X Max = This is the right side of the pool table
Y Max = This is the bottom of the pool table

1. The shot selection algorithm produces a possible shot angle

2. Following the proposed shot angle, extend a line from the edge of the cue ball to the edge of the pool table. This Distance will be the stickExtension.
   Finding this distance algorithmically was not as simple as extending out the line though.
    a. Determine the quadrant 1 through 4
    b. Create a small triangle inside of the pool ball, use the radius as the hypotenuse and the given angle, then use *sin* and *cos* for coming up with the x and y distances

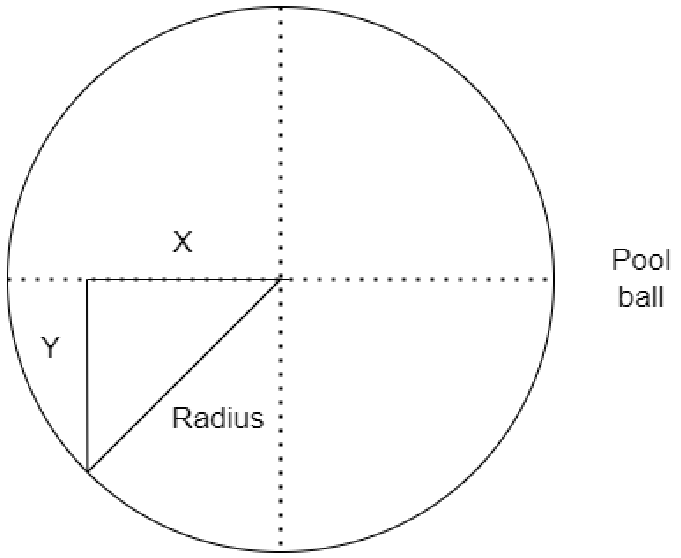


Figure 6.2 Shot Angle Projection

    c. Depending on the quadrant, VISION will find the minimum distance from the center of the pool ball to the corresponding x and y value for the side of the table. This is called the minimum difference. VISION also records the corresponding axis, x or y, and calls this the minimum difference axis.

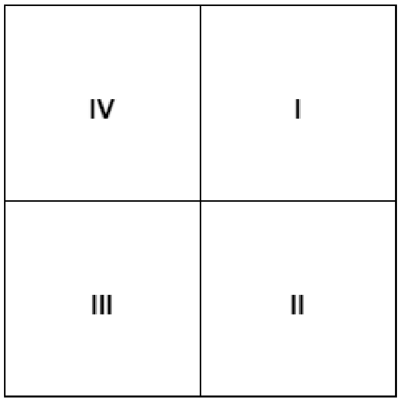


Figure 6.3: Shot Angle Quadrant

- i. Quadrant I: 0 for y, max for x
- ii. Quadrant II: max for y, max for x
- iii. Quadrant III: max for y, 0 for x
- iv. Quadrant IV: min for y, min for x

- d. Divide the minimum difference by the corresponding length on the minimum difference axis of the small triangle. This provides the extension factor
- e. Multiply the radius of the pool ball by the extension factor and subtract one radius from it, this provides the current extension

3. VISION checks to see if stickExtension is greater than stickMax, if it is, the shot will be skipped.

4. Next VISION checks to see if the user's body is in the way of the shot. For this, VISION extends a line the length of userWidth at a 90 degree angle to the left of the stickExtension line. If this line does not intersect with the dimensions of the pool table, the shot is accepted. If it does intercept, VISION will proceed to the next step.

5. VISION will now extend currentExtension to maxExtension beyond the pool table wall. From here VISION extends a perpendicular line the length of userWidth to the left of the maxExtension line, if this line still intersects the table, the shot is skipped, otherwise the shot is deemed acceptable.

A separate algorithm which determines if the pool cue can move without the interference of another ball. This algorithm requires more advanced geometry. Similar algorithms are found in many 2D games and are the basis for VISION's approach. Raycasting is used in many games and a similar algorithm is used to ensure that the shot does not intersect with other balls.

1. The cue ball position will be deconstructed into its x and y position
2. Create a unit vector
    - a. unit vector x = *cos*(shot angle)

```
        b. unit vector y = $sin$(shot angle)
    3. Loop through every ball on the table currently
        a. Take the ball_x and ball_y from the ball
        b. Create a vector from the origin to the ball
            i. Origin_to_ball_vector = (origin_x - ball_x, origin_y - ball_y)
        c. Get the magnitude of the bal vector
            i. Magnitude ball vector
               = $\sqrt{(origin\ to\ ball\ vector\ x)^2 \ - \ (origin\ to\ ball\ vector\ y)^2}$
        d. Compute the intersection
            i. Intersection = unit vector x * origin to ball vector x + unit vector y
               * origin to ball vector y
        e. Calculate  interaction length
            i. Intersection length
               = $\sqrt{(magnitude\ ball\ vector)^2 \ - \ (intersection)^2}$
        f. If the intersection is greater than the radius of the ball then the raycast
           intersects
```

Modifying of "PoolGenius": The open source project used for VISION was described in section 3.2.1. While there were several issues with this software, it was decided that there are several factors making a high accuracy simulation and shot selection algorithm unnecessary. The uncertainty of the player being able to perfectly match the force and the angle make detailed strategic planning unnessecary. What is needed is believable simulation of collisions which produce shot selections which a real player would see as logical. Pool Genius already has a collision system and AI, VISION will be making the following modifications:

- Set the simulation table state to the real table state after every shot. This can be accomplished by changing the program to taking in the current table state and then producing a shot before closing
- Implement the algorithm to see if the shot is reachable by the player
- Implement the algorithm to ensure the pool cue is not be blocked

Below is a UML class diagram describing the design plan for integrating the constraints with the PoolGenius software. This UML diagram focuses on parts VISION will be implementing in conjunction with the simulation system used. Only relevant classes and functions are shown due to the large nature of the software. The RealisticAI class inherits from the base PoolAI class in order to communicate with the existing simulations run by another physics software known as Box2D. The drawable class will have another function in order to draw a pool cue, this will allow for the GUI to better show the desired shot angle. There are two functions which will be added to the software, one is test_mode which allows for the GUI to be active and the other is production_mode which will run more efficiently without the GUI overhead. The test_mode function also allows for results to be verified in an easier fashion.

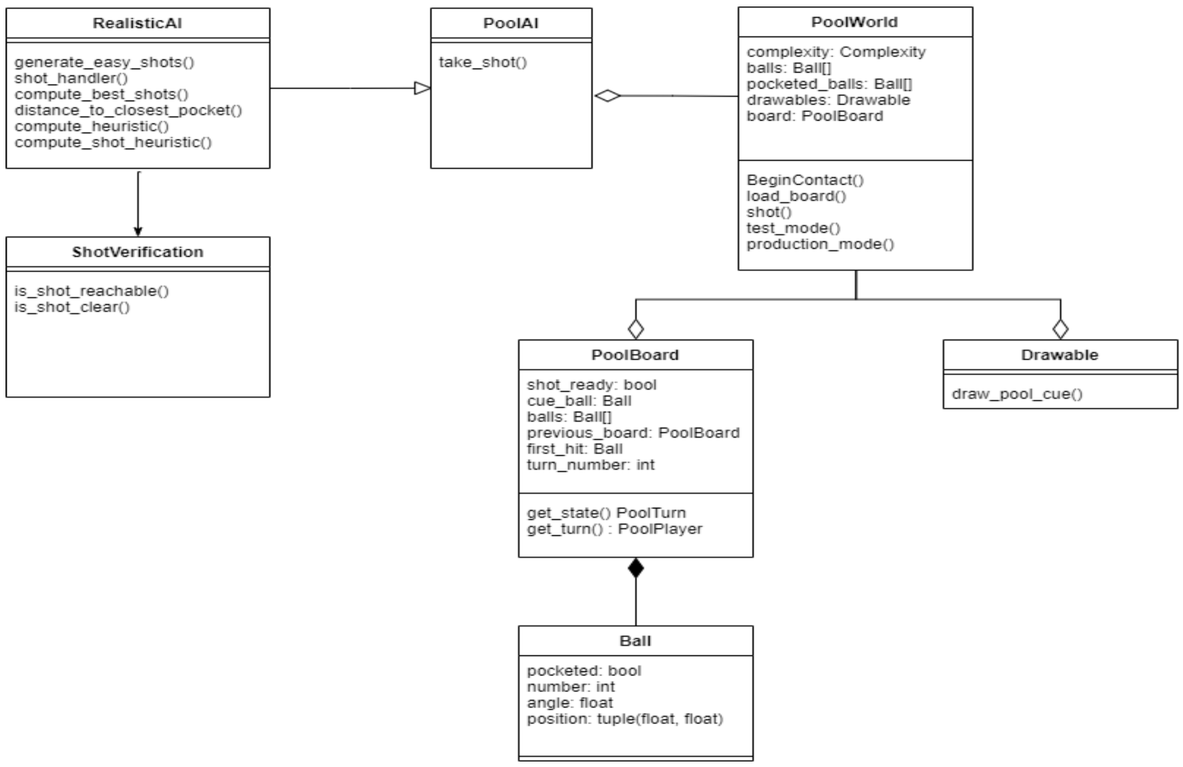


Figure 6.4: High-Level Overview of Shot Selection System

6.3 Localization and Guidance Algorithm Design

VISION's core goal is to navigate an impaired user to a desired location. The following is the design in place to make this primary goal a reality.

6.3.1 Localization Algorithm Design

Swift App to Jetson Nano: The primary means of communication between the Swift App and the Jetson Nano is MQTT through a free test server from EMQX. This was chosen because of available packages on Swift/Xcode called CocoaMQTT which were already incorporated in VISION's application. All iPhones have connectivity to the internet, so this was not a worry for user testing. MQTT allows the users iPhone and the Jetson Nano to both subscribe to a shared topic. The users iPhone will post the beacon distances to the shared MQTT topic every second. A separate thread of VISION will be running that waits on a notifcaiton from the MQTT server to let it know that a new message has been received. When a new message is received, the MQTT thread will convert the distances to the two closest speakers. The unit of speakers is used so that a common form of distance can be used between the user localization and user guidance system. Once three sets of distances have been collected, an algorithm will be run to determine if a clear location of the user is discovered. The algorithm considers how many distinct speakers have been collected from the MQTT messages. There is a total of six total speaker entries, three iterations which each iteration providing two speakers. If there are four or more distinct speakers in the list, the localization process is repeated. If there are three or less distinct speakers, the two speakers with the most occurrences are determined to be the closest speakers. In the event of a three-way tie, the localization process is repeated.

In order to communicate between the MQTT thread and the main VISION thread, a simple lock is used as a synchronization mechanism. When the MQTT thread has a new location to inform the main thread about, it acquires a shared lock and sets a shared flag to let the main thread know that new data is available. The updated position is written to a shared variable and then the lock is released. If the main VISION thread is attempting to get a new user location, it will attempt to acquire the shared lock. Once the thread acquires the lock it will check if the shared flag is set to indicate that there is new data. If there is new data, the thread reads in the new data and lowers the flag. If there is not new data, the thread sleeps for a second and then restarts the process. This architecture allows for the MQTT thread to constantly aquire new data from the Swift application running on the user's iPhone. The MQTT thread will continue to update while other parts of VISION are running (computer vision or artificial intelligence algorithms), or when VISION is waiting on the SCRATCH team.

Trilateration: The MQTT thread converts the distance coordinates in the chosen (x,y) coordinate system using trilateration. The trilateration code relies on provided initial positions of the beacons and reported distances between the beacons and the user’s iPhone. The outcome of the trilateration code is an unfiltered raw user position. This position is raw in the sense that the application sending distances every second can be subject to inaccuracies within the centimeter range as advertised by the company. To combat these inaccuracies, VISION smoothes and averages the values over nine seconds to obtain a more precise position of the user. The user’s position is then filtered to account for the presence of the pool table which is unknown by both the beacons and the trilateration code. This filtering restricts the position returned to either corner of the pool table by determining which edge the user is closest to. The restriction is done by computing the distance between the user’s smoothed, unfiltered position and their potential position if it existed under any of the edges. For instance, assume the user is located at (x,y), their potential positions on the edges are:

- Top edge: (x,0)
- Bottom edge: (x, max y)
- Left edge: (0,y)
- Right edge: (max x, y)

This allows VISION to make a more precise decision as to where the user is located. The next part of this process is then to determine which speakers are closest to the user to convert the user’s position in terms of feet to a speaker position. This scheme is done in similar fashion to the beacon technique described before in that the two closest speakers are the ones that return the shortest distance to the user’s position. However, VISION has to filter these speakers out once again account for any inaccuracies from the system, from the user moving, or even from the very close position of the speakers. From this point, the user's current speaker position is ready to be used by the guidance system.

6.4.2 User Guidance System

Communicating with the PCB (ESP32): In order for VISION to communicate with the speaker array, the Jetson Nano has to send commands to the ESP32 located on the PCB. The communication channel for allowing these two devices to connect is BLE which allows for a lightweight, fast, and reliable communication. By default, BLE supports sending byte arrays between devices, and tends to work better for smaller messages. To reduce latency and computation between the Jetson Nano and the PCB, a simple protocol was developed for sending BLE messages. The Jetson Nano will primarily be sending messages to the PCB, so a state machine was developed on the PCB. The command *PLAY_SPEAKERS* is sent by the Jetson Nano with two subsequent arguments. The two arguments correspond to the two speakers for the PCB to play in an infinite loop. The Jetson Nano can also send the command *STOP_SPEAKERS* which will stop the PCB from playing any speakers. The PCB offers a simple communication interface to the Jetson Nano that can be used for many different purposes. The PCB does not respond to messages from the Jetson Nano but can transmit a *PAUSE* signal to the Jetson Nano to let the main VISION program know that the user needs a break. When this signal is received, the VISION program simply sleeps until a *START* signal is received from the PCB. The PCB can also send a *STOP* signal that will simply kill the VISION program.

Navigation Algorithm: The navigation algorithm for the user is the most important factor of the user guidance system. Some of the goals of this subsystem are to keep the user safe, not overstimulate the user with too many sounds, navigate the user to a desired location within a foot of accuracy, and orient the user within 15° of the desired shooting angle.

In order to keep the user safe while navigating them around the billiards table the navigation algorithm does not attempt to have the user walk around or over the camera stand. The camera stand is a vital position of the computer vision system but does create an obstruction for the visually impaired user while navigating around the table. For this reason, the navigation algorithm will choose a route that takes a longer distance if it stops the user from trying to navigate around the camera stand.

In order to guide the user to the desired location without overstimulating the user with too many sounds, a lot of testing was done to create a speaker sound that is unique but overbearing to a player. A speaker will be turned on and utilize a digitally generated square PWM signal producing a desired output for the user with a duty cycle of 50%. Using the signal with the speakers creates a distinguishable beeping sounds that is able to be identified even in a room with many people talking and other audio distractions.
When navigating a user around the billiards table, VISION primarily relies on the corner speaker to navigate the user to the desired position. Once the initial location of the user has been determined, an algorithm takes in the current location of the user (from the user

localization system) and the desired location of the user (from the artificial intelligence system) and determine the next speakers to play. If the user is already on the correct side of the table, the next speakers to play will simply be the closest speakers to the users desired position. If the desired location is closest to a single speaker, than VISION will send a command to the PCB to play speakers and will specify the closest speaker twice (so that only) a single speaker will be playing. If the desired location is between two speakers, then VISION will send a command to the PCB to play speakers and specify the two closest speakers to play. If the user is not already on the correct side of the table, or the user is on the side of the table where the camera stand is, then the next speaker to play will be the next closest corner speaker in the direction that the user needs to travel. Once the user arrives to the next closest corner, the user localization system will update the user's current position to let VISION know that the user is at the corner. This process will repeat until the user arrives at the final target speaker where they will actually be taking the shot.

In order for the user to know what they should be doing at each step of this process, the Swift application is able to provide instructions to the user based on which step of the guidance process they are in. When VISION is guiding a user to a corner speaker or the final target speaker, VISION can send a message wo the Swift application, through MQTT, asking the application to inform the user to walk towards the speaker that is going to begin playing soon. The Swift application only provides small instructions at key portions of the navigation process to ensure that the user knows what they should be doing.

Once the user localization system has updated the user's position to indicate that they are in the target position to be able to make the shot, the next phase of user guidance can begin. The next step in guiding the user is rotating the user so they are facing the general direction of the billiards ball they are going to attempt to hit. In order to rotate the user in the proper direction, an algorithm will take in the current location of the user as well as the relative angle (from the artificial intelligence system) to determine which speaker is closest in direction to the angle the user needs to face. The orientation of the speakers allows for a maximum margin of error of 8°, so the speaker array can be reused in order to orient the user as well. Once the desired speaker has been determined from the orientation algorithm, the Jetson Nano will send a command to the PCB requested either a single speaker or pair of speakers to be played. VISION will send a message through MQTT to the Swift application that will give the user the next command. The command will request the player to rotate towards the following speaker without moving from the position they are currently standing in. The speaker(s) will play ten seconds to allow the user enough time to hear the speaker(s), determine the direction of the sound, and orient themselves towards the sound. The VISION team tested many different speaker durations and found that ten seconds is sufficient time for the player to orient themselves without delaying the flow of the game too much.

At this point VISION is ready to hand control over to SCRATCH. VISION will communicate to the SCRATCH team over a new MQTT connection and provide the

SCRATCH team with the relative force and relative angle. Once SCRATCH has completed the shot, control will return to VISION for shot feedback.

6.4 Shot Feedback (Computer Vision System)

Once the shot has been taken, VISION will provide feedback to the user to provide them with the outcome of their shot. The possible shot outcomes are that the user did not make any balls, the user made their game ball, the user made their opponent’s game ball, the user scratched (made the cue ball), the user made their game ball early and lost, and that the user made their black ball and won. VISION will determine the outcome of a shot by storing the previous ball list and taking a new picture of the table to determine the current ball list. The current ball list is compared to the previous ball list to determine what the outcome of the user’s shot is. VISION will then convey this information to the user by sending a message to the Swift application which will tell the user the results of their shot. It is possible for more than one outcome of a shot to be true at once. For example, the user can sink their game ball and the cue ball in a single shot.

7. SYSTEM FABRICATION

With the extensive physical and design footprint of the VISION apparatus, a fabrication plan is put forth for both PCB and the full system.

7.1 PCB Design

To properly integrate the circuitry components of VISION and satisfy a simplistic design for integration, several core components will be conjoined through a printed circuit board (PCB). The following section provides details on how the design will be conducted and the best practices to provide a functioning product. For the purposes of VISION, the PCB was designed in Altium for its simple user interface and because it is free for students at UCF. The majority of components that will be built into the PCB can be accessed using the Altium libraries, imported libraries from distributors such as Digikey and Mouser, and custom components when needed.

7.1.1 PCB Design Philosophy

The following outlines important practices in PCB design as outlined from Altium, one of the leading PCB development software companies. (Peterson)

Component Placement: Component placement is where PCB begins and can be fine tuned throughout the process of development. The goals for a well placed board should focus on ease in routing and limiting layer changes when possible. Several good practices to ensure a proper layout consist of prioritizing placing must-have components first and large processors/ICs in central locations, avoiding net crossing, placing all surface mount devices on one side of the board, and experimenting with different orientations of components. Following these steps and focusing on the largest and biggest hassle components first can limit headaches and improve design throughout the PCB design process.

Power Planes: Following the placement of components, the orientation of the power and ground planes is the next focus. Power and ground are placed on two internal layers, which can be a hindrance with only two layers. The ground plane is ideally on its own layer and is not recommended to route ground traces on a board. Power is recommended to be implemented via common rails connected directly to the power source, but power planes can also be implemented if components do not get daisy chained and have wide enough traces.

Routing: Determining the proper routes for connections between components can be an artform and is up to the designers discretion. Ideally, short and direct routes are highly recommended. An important rule to follow is if all the traces on one side of the board flow in one direction (horizontal), the other side should flow all traces the opposite direction (vertical) to restrict emf disruption along traces. This is very important in two layer designs, and should alternate between layers in multi-layered board designs. Certain special case designs will require added practices to account for specialized component characteristics. Additionally, determining the proper width for traces can be a complex process, but can be determined by analyzing the manufacturability, current consumption, and impedance that will be seen through the design.

<u>*Component Grouping:*</u> Guidelines on grouping and separation can be valuable to ensure easy routing, prevention of electrical interference, and thermal management. At the heart of component grouping is placing items that are in a circuit together, especially if they do not interact with other portions of the board. Separating analog and digital components is a very important step in grouping, and can prevent commonly introduced interference. If these grouping practices are followed, the design becomes an exercise in placing groups rather than individual components. An important note in the grouping process is the separation of high powered components, as close proximity can lead to thermal issues.

7.1.2 PCB Design

The components of VISION included within the project's PCB are centered around the guidance output system and the user control interface. This encompasses a connection to the Jetson Nano, outputs to each speaker, regulators for both voltage and signal output control, a demultiplexer for signal selection, and push buttons for the control interface. Included in the PCB are the following major subsystems and components:

- Connection to Jetson Nano
- ESP32 Chip
- Switching Regulator
- Audio Amplifier
- 12 Speaker Outputs
- Demultiplexer (CD74HC4067)
- Five Push Buttons (One Extra Button)

Figure 7.1 shows a block diagram of the systems included in the PCB design. Figure 7.2 shows VISION's final PCB design.

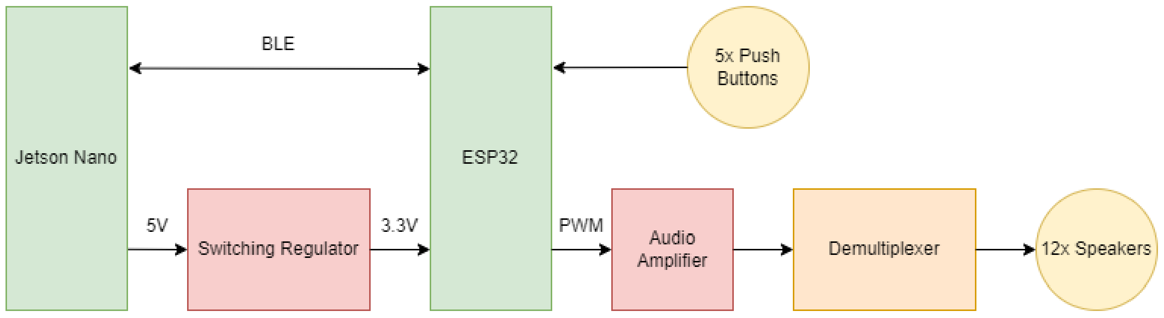


Figure 7.1 PCB Design Block Diagram

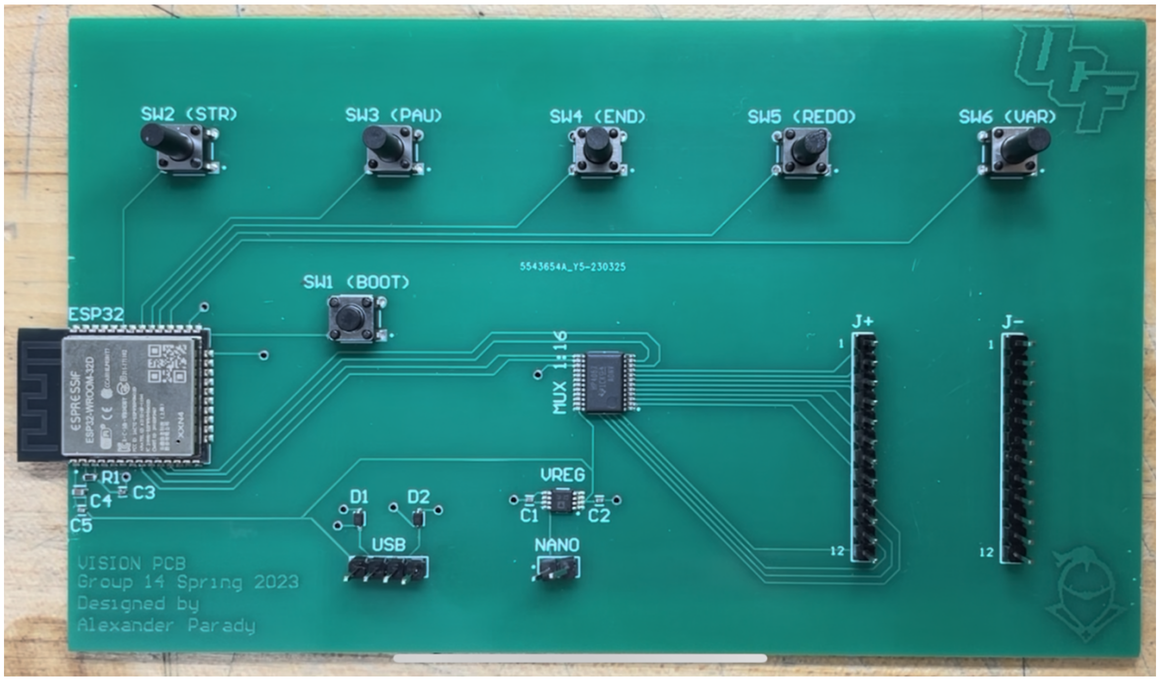


Figure 7.2 Final VISION PCB Design

8. SYSTEM TESTING PLAN

The following two sections focus on the hardware and software side testing for VISION. To properly meet the goals set out by the project, the team must successfully validate each system to standard tests. If standards are not met regarding these testing guidelines, changes to design must be made accordingly to properly deliver on the project's mission.

8.1 Hardware Testing

8.1.1 Guidance Testing

As guidance is at the core of VISION, its validation is critical to the validity of the system at large. VISION's design relies on audio guidance mechanisms in the form of speakers. To properly validate these, several important scopes should be examined and tested.

First, the proper output signal must be generated and validated to an ideal signal strength that is receivable by the human ear and loud enough to be differentiated in a crowded room. To do this, the signal is played in a room with artificial noise being introduced. If the examiner can distinctly hear the audio being generated, the waveform is validated.

The efficacy of the guidance mechanism must be placed under rigorous testing following the validation of perceivable sound. To do this, a simulated impaired user (blindfolded team member) is used in both the case of positioning and orientation guidance. To validate positioning guidance, the user was able to follow basic commands from the speaker array. The efficacy of these commands were examined on both their validity in general positioning, their ability to cease use after arrival, and the accuracy of the positioning within the proposed margin of error of six inches. Examining the orientation mechanism then follows this stage, and involves validating the expected output signal, proper speaker outputs, and that the user can be oriented within the 15° margin of error based on the target orientation and actual orientation.

The end goal of this validation scheme is verifying that the user is positioned accurately enough that the user can be guided by the SCRATCH system to commence final guidance and execute the shot.

Finally, the most crucial test will be conducted in seeing how accurate the fully integrated system design is. The number of successful iterations of VISION was recorded over a number of varying test cases. This number of successes was high enough that the guidance system for VISION was considered a success.

8.1.2 UWB Testing

There is no significant hardware testing to be done in the localization system since all testing can be done on the software side. The main physical testing that can be described is making sure that the user was properly localized, and within the defined accuracy of 1 foot. To perform this testing, at different stages of the software design, the VISION team compared the distance returned from the beacons to the Swift application distances to confirm that the advertised accuracy from the Estimote company was correct (in the order of centimeters). From there, the accuracy of trilateration, smoothing, filtering, and position to speaker conversion were all tested for correctness.

8.2 Software Testing

8.2.1 Shot Selection Algorithm Testing

In order to ensure that the shot selection algorithm produces consistent and valid results, several test cases were run to ensure the user is not prompted to do a task which is either impossible or illogical. Many of the test cases corresponds with the the section discussgin edge case behavior. The testing will feature three approaches.

- Programmatic Testing - Testing will be done after any change to the code is made, results will come back quickly and will give rapid feedback on any breaking changes.
- Simulation validation - Visually verify that the results from the shot selection algorithm make sense from the display. This should be done after any major changes to the system.
- Physical Testing - Verify that the shot selection algorithm produces shots which are comfortable and realistic to attempt. This should be attempted sparingly, but at least one successful run should be made before any overall system tests are performed.

<u>Testing shot selection:</u> There will be several test cases that have an obvious correct answer. Ensuring that a correct decision is made on an obvious table state is of extreme importance and points to a reliable algorithm. The testing will feature a simulation that goes along with the shot selection, the table state will be provided to both the simulation and the shot selection algorithm. A success of the test case will be when the simulation executes the shot selection algorithm and makes the desired ball. The following test cases will be verified for each pocket on the table:

1. Ball and cue lined up in front of a pocket.
   Pass: Shot made
   Fail: Scratch or no made shot
2. Simple bank shot
   Pass: Shot made
   Fail: Scratch or no made shot
3. No easily makeable shot

Pass: No scratch
Fail: Scratch

<u>Physical Limitation Tests:</u> These tests focus on ensuring that the physical limitations of the player are respected in order to give achievable shots. The test cases should cover the previous shot selections as well as a test passing for shot selection but not being possible is a poor indicator of our software quality. The following test cases will be verified:

Pass: The shot conforms to physical limitations as listed above
Fail: The shot fails to conform to physical limitations

1. Shot selection tests for right handed player
2. Shot selection tests for left handed player

8.2.2 Computer Vision Software Testing

The computer vision system is the initial input to the project, so the system must function accurately so errors are not propagated to other systems. The difficulty in testing the computer vision system stems from the nature of billiards itself. There are an infinite number of ways that the billiard balls can arrange themselves on the table, so it is not feasible to test every possible input configuration. The testing procedures will include the most common scenarios that a player might encounter and a few edge cases. As the project progressed, test cases were added to ensure that the computer vision system is functioning properly. This section outlines some of the most prevalent scenarios that were tested but are by no means comprehensive of all possible input scenarios.

<u>Testing the Billiard Table Isolation:</u> The billiard table isolation feature of the computer vision system is the simplest feature to test. This feature is responsible for separating the playable region of the billiard's table from the input image. The output for tests related to this feature should all have nearly the same output. The output should include a rectangular contour outlining the playable region. The testable output will contain the minimum and maximum x-coordinates and y-coordinates. Although the outputs of this system may not be the same for every iteration, the values can easily be checked for reliability once baseline values were established.

<u>Testing for Finding the Billiard Balls:</u> The feature responsible for finding all of the billiard balls on the table will be the most complicated feature to test. This feature includes detecting all the billiard balls in the image, determining the coordinates of the billiard balls, and determining the color of the billiard balls. This position of the computer vision system is also responsible for identifying and ignoring false positives in the input image. The output of tests related to this feature will be the information appended to the output list. This section will append the type of ball found (cue ball, black ball, blue ball, or green ball), the localized x-coordinate, and the localized y-coordinate for every billiard ball in the input image.

Before discussing how to create unit tests for this feature, a brief discussion on testing for the minimum and maximum radius is needed. Section 3.2.2 describes utilizing the parameters available in OpenCV's Hough Circle Transform to specify the minimum and maximum radius. To determine the minimum and maximum radius, other built-in OpenCV features were used. By running the Hough Transform without any radius requirements, all of the circles in the image will be discovered. The discovered contours were manually iterated and highlighted so each contour can be verified for correctness. The area of all of the correct contours was then be found by using an OpenCV area method. Once a substantial amount of samples were collected, the average radius, in pixels, was extracted from the area measurements. An appropriate radius threshold was then set.

Testing this feature is ensuring that the output list is updated properly to reflect the current state of the billiard table. To ensure that the feature is working properly, simple testing was conducted and more complex scenarios were added after simple functionality was proven to work. Simple tests of the system included capturing input images where billiard balls are on the table in a variety of configurations. The output list should accurately represent the number, color, and location of the types of balls on the table. It was important to consider lots of different combinations of inputs. Once the basic scenarios were verified to be working properly, more complex scenarios were added. Important scenarios to consider were when the white ball was not present, the black ball was not present, neither the black ball nor the white ball were present, and when no balls were present. Other, more complex, scenarios were when two or more balls were touching, the cue stick was present in the input image, and when there were circular objects in the input image that are too small or too big to be billiard balls. All of these scenarios were considered in different lighting conditions to ensure that the accuracy of the computer vision system is not diminished by different lighting conditions.

A set of automated unit tests were created by capturing many input images representative of the previously described testing scenarios. Generating a suite of unit tests ensured that the system is functioning as expected. These unit tests have a verified output list associated with each input image so that any changes to the computer vision system can quickly be verified against an established set of tests. Creating such a testing environment was important because it will allow for changes to the project to be verified quickly, without having to manually test the new modifications.

8.2.3 Feedback System Software Testing

Testing the Shot Result Feedback: Testing the shot result logic of the feedback system was one of the most important features to test in the project. The shot result subsystem should be able to take the previous and current state of the billiard table and determine the outcome of a player's shot. This subsystem is straightforward and can be easily tested. The inputs for the feedback are two lists originating from the computer vision system. One of the lists was the previous state of the billiard table and the other list was the current state of the billiard table. It is possible to create test lists representative of all possible scenarios the computer vision system can output. Once created, theselists will form a test suite used against the expected output ensuring that the system was functioning properly.

The actual testing of the shot result feedback consisted of checking if the cue ball was present, if the eight ball was present, how many green balls were present, and how many blue balls were present. If the eight ball is present, then the user has either won or lost the game. The deciding factor is if the player has any game balls left on the table. If the eight ball is not present, the user will continue playing and has either not sunk a ball, sunk their game ball, or sunk an opponent's game ball. All of these scenarios are predictable and can be tested easily with custom input lists.

8.2.4 Localization Software Testing

This section talks about some of the testing that was done to the code itself during conception and until completion. Brief outlines of this were described in the hardware testing section but this section goes in more depth on the topic.. To begin with, the trilateration code was heavily tested in two different ways. The first testing method was where 2D to 3D trilateration was compared to determine which of the two was more effective and precise. The main difference is that in addition to providing x,y positions of the beacons, like in the case for 2D trilateration, the 3D version of the code also needs the height or z-position of the beacons. The z-position is how far off the ground the beacons are on the pool table. It was realized that that the beacons were all designed to be at the same level, 3D and 2D trilateration codes returned the exact same position. For simplicity, 2D trilateration was chosen for the rest of the project. VISION also experimented with the aforementioned position of the beacons. Initially designed to be perfectly centered at the start of the coordinate system i.e. (0,0), (X_MAX, 0) and (X_MAX/2, Y_MAX/2), the beacon positions were then offset slightly to account for the distance readings reporting a distance offset that did not align with the VISION team's coordinate system. This offset position also took into account the results from trilateration to make the computed position more reliable especially at the corners of the pool table that proved to be the most difficult parts of the table to locate.

The second portion of this testing can be summarized under the smoothing portion of the code. Smoothing attempts started at the conception of the Swift application where VISION attempted to average the distance every 3 seconds before sending the distances through MQTT. The goal of smoothing is to provide more reliability to the transmitted data. For simplicity, after testing and smoothing in other positions, VISION opted to send the distances every second instead to get better readings of the application. After these distances were sent, they were then converted to x,y positions as described earlier. However, being computed every second, these distances were not accurate enough and noticeably flucuated. For this reason, the team decided to average out the distances over nine seconds and rely on this average value as the user position. The filtering portion of the code through physical testing was also tested. These tests determined if the filtering code worked on either side of the pool table and at the difficult corners where either edge could be chosen. The edge issue was the biggest concern for the team, but the concern was mitigated once VISION decided to turn the user positions directly into speaker numbers. Additionally, the program selects the two closest speakers user. Having two possible speakers made the VISION team consider averaging out and finding a mode or the two most frequent speakers returned after three computations were performed. This design allowed VISION to offset cases were any part of the code until this point might lead to incorrect results. The use of a mode allows for VISION to account for the corner cases since the two closest speakers would be on the two possible table edges. Utilizing two speakers also allows the team to account for the very close distance between the speakers (about a foot). Another concern was when the beacons would stop being responsive after a period of time. To mitigate this issues, the team implemented audio feedback for the user letting them know to move their phone around since the issue happened when the phone was stationary for too long.

Other components of the localization system that would required additional testing are the battery life of the beacons (considering they cannot be turned off) and the ideal location of the user's iPhone to maximize the accuracy of trilateration. For the first point, the battery life of the beacons were advertised to be up to two years which exceeds the timespan of this project from conception to completion and hence did not end up being an issue for VISION. For the second point, there are a few options for the user to hold the phone without it being an issue for the duration of the pool game. Currently the localization system has the user holding their phone while they are being localized. Other options were tested such as having the iPhone in the user's pocket and using a band (similar to what runners use) that the user can wear. No significant difference of location was observed to warrant one of these over the other. The VISION team decided to leave the decision of the user's phone position to the user themselves, as long as it is adequately in line with the user and not in a completely obscure area.

8.3 User Testing

To evaluate the success of VISION and SCRATCH, a visually impaired user should be navigated around the billiards table and able to successfully complete a clear shot. The success of the projects largely depends on a user's ability to complete a shot. If the system created by VISION and SCRATCH can allow a user to sink a billiard ball, the system will be considered successful.

From VISION's perspective, the first benchmark is being able to properly capture the state of the billiard's table and represent the table state computationally. The table representation should also be able to produce a reasonable shot selection with the help of the billiards artificial intelligence system. This process is not easily verifiable and required the VISION team to manually verify the shots. The table representation was verified to ensure that the representation accurately reflects the state of the table. The shot selection was verified to ensure that the artificial intelligence algorithm selects a shot that is feasible and guides the user to progress towards winning the game. These verifications were performed by testing the system with an actual user and verifying VISION's decisions in real-time.

The second benchmark of VISION is being able to locate and guide the user around the billiards table. The user's location was checked against the location of the user that VISION reports to the system. The user was within the allowable distance of the user localization system, the system was deemed a success. The user guidance should be able to guide a user around the billiards table from a starting location to a final location. The system was tested by guiding a user from some starting location to some predetermined final location. The user was able to be guided to the final location within the specified margin of error, the user guidance system was considered successful.

Overall, there was no automatic way to test the effectiveness of VISION. Individual test cases were designed for each subsystem to validate the subsystems basic behavior. Success during individual testing did not correlate to success of the overall project. The project was validated by testing the entire system and verifying the system's results in real-time. Subsystem testing helped to eliminate major subsystem issues, but the true test of VISION occured when all of the subsystems were integrated and able to guide a user to a desired position and provide the user with feedback on their simulated shot

9. User Guide

9.1 Operation Overview

This manual is separated into two parts. The first part describes how a visually impaired user operates the system. The second part covers the tasks required of the game assistant to ensure smooth functioning over the course of the game. The game assistant is necessary for the current version of the system but will be removed in future iterations. The VISION team believes that many tasks of the game assistant can be automated away, giving the visually impaired user more freedom. The technology required to automate all of the assistant tasks is beyond the scope of the current project. The operation overview also assumes that the pool table has been installed with the proper equipment, as described in the previous sections. The pool table should have the 12 speakers mounted and wired around the table. The table should also have the assembled PCB firmly attached to the underside. Another crucial component is the camera mount being constructed to the specified dimensions.

9.2 Project User Guide

VISION is the first part of a two-team project that allows visually impaired users to play a game of billiards. This section focuses on how a visually impaired user goes through the process of playing a billiards game on the system. It takes the user through startup, moving to a shot, taking the shot, and listening for the shot result. There is also a section about dealing with possible issues or bugs in the system.

9.2.1 Startup

The startup process is controlled mainly by the assistant. However, the system will give the player audio queues to know the current step in the process. Informing the player gives them more freedom and allows for a more enjoyable experience. The assistant will hand the player a phone with the localization app running. The app is responsible for tracking the player's current location in regard to the table. The app also gives the player audio queues and instructions. When the assistant starts the game, the user will hear the phone output: "*User localization in progress*". At this stage the player will know that the game has started and will be ready to execute the next set of instructions.

9.2.2 Moving to a Shot

After the assistant has started the game, the computer vision system will scan the table and then the shot selection AI will select a shot for the user to take. There is a direct communication between the app on the user's phone and the Jetson Nano, this allows the user to be localized in real time. The user can be tracked anywhere around the room as long as the application is running. Using that user's position and the result from the shot selection AI, the system guides the user towards the speaker(s) nearest to the ideal shot. The localization app on the phone uses the audio cue, "*Move towards the speaker*", after this cue, a speaker will play. The user should slowly move along the perimeter of the table towards the beeping speaker. The best method for moving around the table is to take smaller steps and to keep one hand on the table and use the other hand to hold the phone as shown in figure 9.1. The user will continue this while moving parallel to the current wall. It is also recommended that the user stands roughly a foot away from the table to avoid interference with the radio waves or multipath fading as a result of this interference. Once the user has arrived, they will wait (up to 9 seconds) for the localization system to ensure the user is at the correct speaker. This same time delay applies for the intermediate speakers on the way to the nearest speaker for the shot. If for any reason the user moved away from the table or walked to the wrong speaker, the localization system will play another speaker in order to guide the user back towards the table. The localization system mostly relies on the corner speakers to guide the user, the inside speakers are only used for when the user is getting close to the desired location. Once the user has reached the final destination, the localization app will prompt them further.

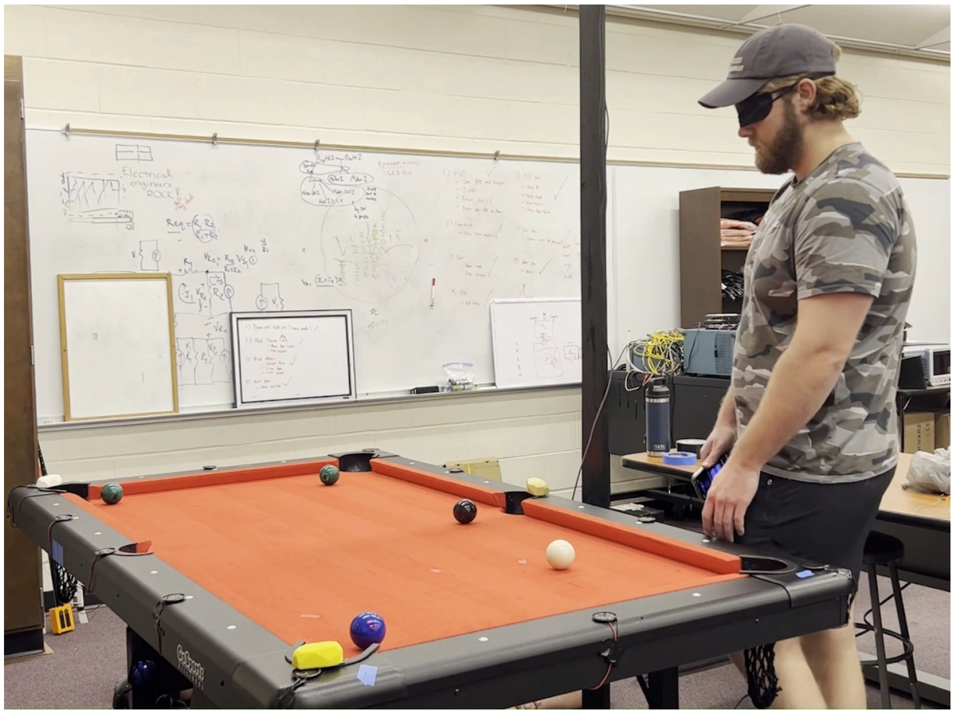


Figure 9.1: User Moving Along Table

9.2.3 Taking the Shot

Once the user has reached the final destination, the localization app will use the following audio prompt, "*Without moving, turn towards the speaker*". After this prompt a speaker will then play for 10 seconds. The user should then try to face directly towards the beeping speaker, angling their entire body in the general direction of the sound as shown in figure 9.2. After this step, the SCRATCH team will take over and further instruct the user on how to make the shot. The reason for turning the user is to allow for them to be oriented in the correct direction within 7.5°. Turning made it much easier for the SCRATCH team to deal with fine grained movement details.

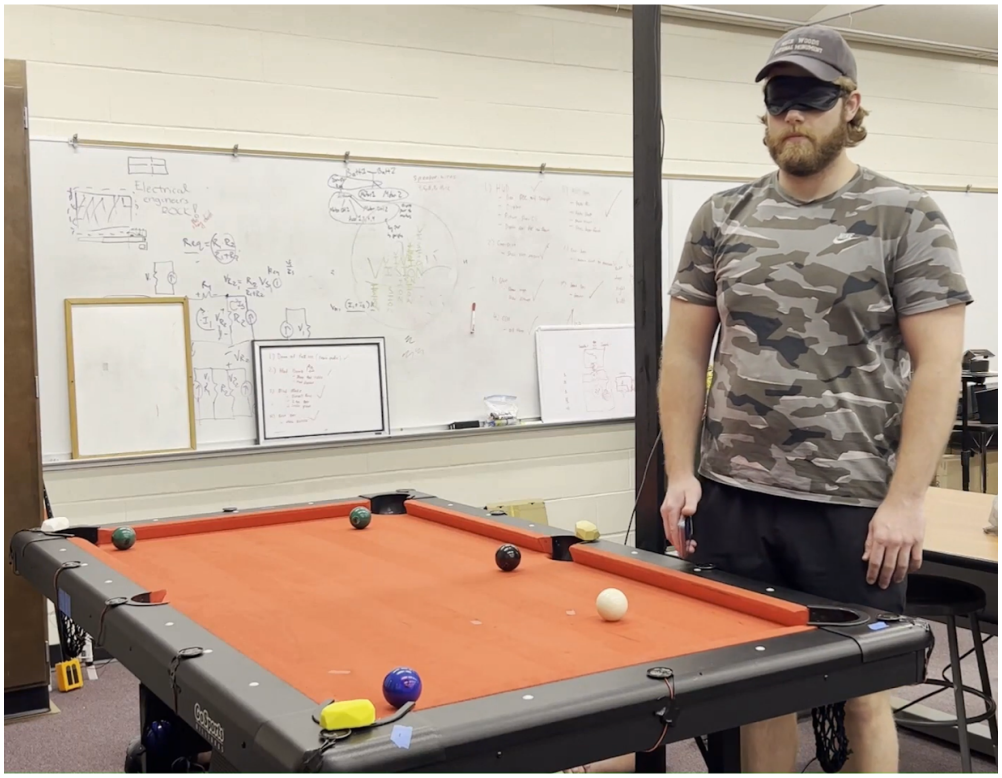


Figure 9.2: User Rotating to Speaker

9.2.4 Shot Result

After the SCRATCH team has guided the user to hit the cue ball, control will return to VISION. The computer vision system will scan the current table and compare it to the table before the shot was taken. The computer vision system then infers if an opponent game ball was made, the user's game ball was made, the user lost, or the user won the game. The user localization app will then use an audio cue such as "*Eightball made with all other game balls made, the user wins*". If the user were to win or lose it would require the assistant to help them restart the game. It is possible for multiple feedback statements to occur after a single show was taken depending upon the outcome of the shot.

Overall, the following audio cues could be heard at any point from the app on the user's phone:

Localization in progress
Localization stopped
User made their game ball

User made an opponent's game ball
Game loss, made black and white ball
Game loss, black ball made before all game balls
Game won, black ball made after all game balls
Scratch, white ball made
No balls made
Walk towards speaker
Without moving, rotate towards the speaker

9.2.5 Troubleshooting

If the user notices a longer delay than normal on the localization system or if the same speaker is beeping no matter where the user is located, the user may first try moving the phone around or slightly moving around the area of the speaker. This process can sometimes help the localization system to recalibrate on the user's current location. Another way to ensure that the user localization system is accurate is to keep the user from holding the phone within the boundaries of the pool table. The player should attempt to keep the phone outside of the walls of the table. The user should also try restarting the app completely if issues persist. The user may also receive more accurate readings by attempting to keep the phone at the same level as the beacons. This would allow the communication between the app and the computer system to be resumed if a communication failure was the issue. If the localization process is still not working and the user is standing next to the beacon for more than 45 seconds, the user should let the assistant know they are having issues.

9.3 Project Assistant Guide

The assistant is responsible for helping the visually impaired user with tasks that are not yet automated. These tasks include ensuring that there are no objects that could impede the users movement, setting up the billiard balls on the table, and starting the game. The assistant is also there to help with trouble shooting in the case of an error by the user localization system.

9.3.1 Startup (Table, Camera Stand, Billiard Balls)

The first step is to set up the actual pool table and camera stand. The easiest way to accomplish this is to have a taped out area for repeated use. The main idea to keep in mind is that the camera stand should remain on the fourth wall slightly over the middle pocket. The exact location should be 32 inches away from the bottom left corner of the pool table, as shown in figure 9.3 below. After the table and camera stand are in place, the assistant will then proceed with placing down the billiard balls into any fashion the player desires. The player may want to practice, meaning that the assistant would set up some easy shots for the player to make or the player may want to play a full game in which the assistant would line up the balls properly into a triangular shape. Once the table is set up, the assistant would start the main VISION program on the Jetson Nano by entering *python3 VISION.py*.

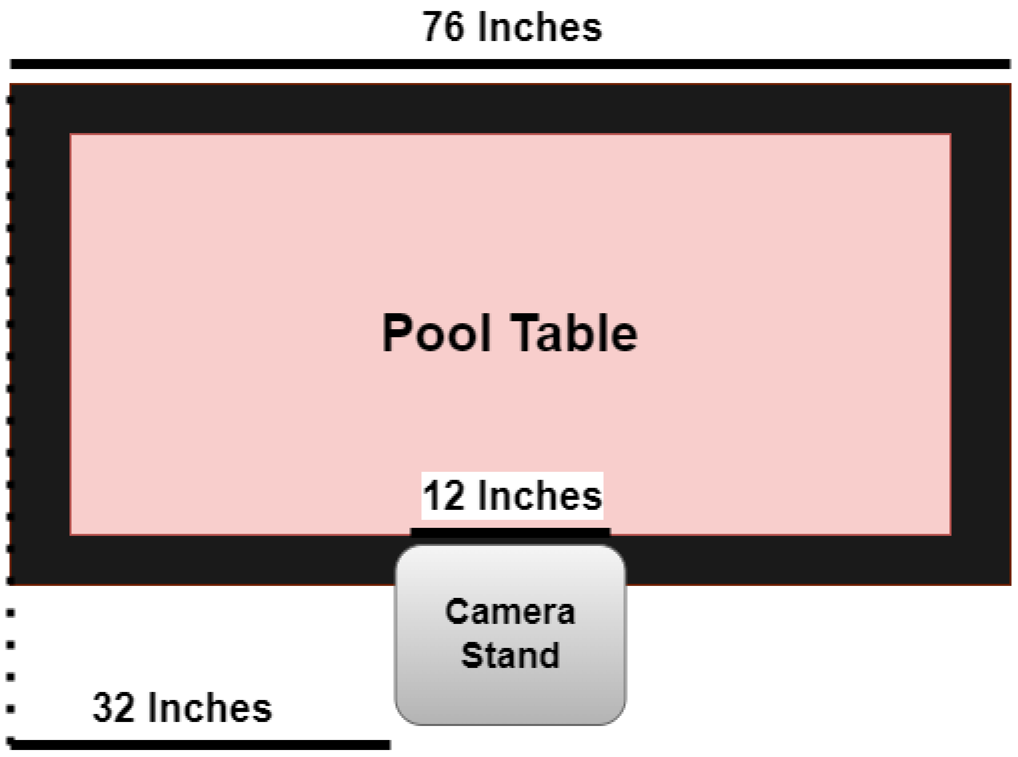


Figure 9.3: Camera Stand Location

9.3.2 Camera and Jetson Nano

After the VISION program is executed, the assistant will ensure that the camera is not blurry and will be able to accurately read the table state. Once the video on the display has finished focusing, the assistant should hit the letter "*q*" on the keyboard. If the camera is not properly cropping the image of the table, the assistant will move the stand to the correct location. If there is significant blur or the camera cannot focus, the assistant can focus the camera by putting their hand towards the camera and slowly moving it down as the camera gradually focuses. After the camera and computer vision are set up, the Jetson Nano will attempt to connect with the user guidance system over Bluetooth low energy and the user localization system over MQTT messages.

9.3.3 User Guidance and PCB

The user guidance system is the system connected to the 12 speakers located around the table and is responsible for guiding the user through audio. The assistant will have to ensure the PCB is plugged into a 5V power source (we recommend using the 5V pin on the Jetson Nano) and then press the start button located on the PCB. The PCB also has a pause and reset button for controlling the game in the case of an issue or for taking a break.

Button Functionality :

SW2 (STR): Start Game
SW3 (PAU): Pause Game
SW4 (END): End Game
SW5 (REDO): Redo a Turn
SW6 (VAR): For Testing Purposes

After the PCB is turned on and the game has started, the assistant should not have to worry about interacting with the PCB again unless it is to start a new game.

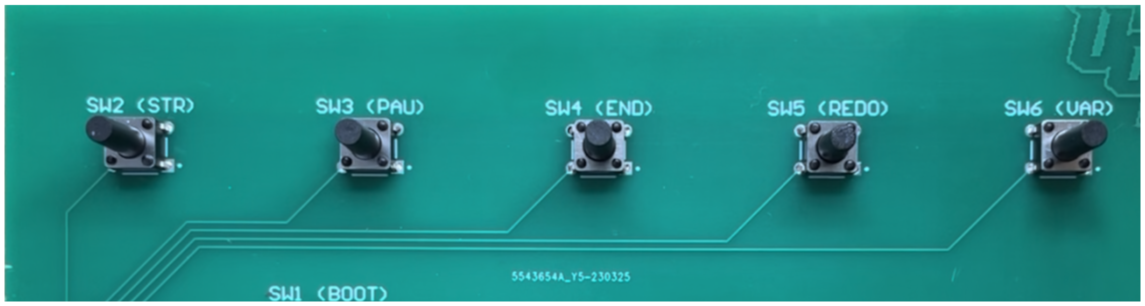


Figure 9.4: User Guidance Buttons

9.3.4 User Localization App and Beacons

The first step for setting up the user localization system is to place the beacons around the table. The top left and top right corner should each have a beacon placed directly next to the speaker. The remaining beacon should be placed in the middle of the bottom wall, directly next to the middle pocket speaker and camera stand as shown in figure 9.5. After the beacons have been placed, the assistant will then open up the user localization (VISION) application and press start for the user. The user should be able to function on their own after this point. If at any time it appears that the user localization system is not properly tracking the user, the assistant may attempt to remedy it by taking the phone and hovering it above each beacon. This movement often allows any location updating issues to be solved. The phone application shows the distance between the phone and each beacon. If the assistant notices that the distance for any single beacon is not changing, the assistant may attempt to move the phone over the particular beacon.

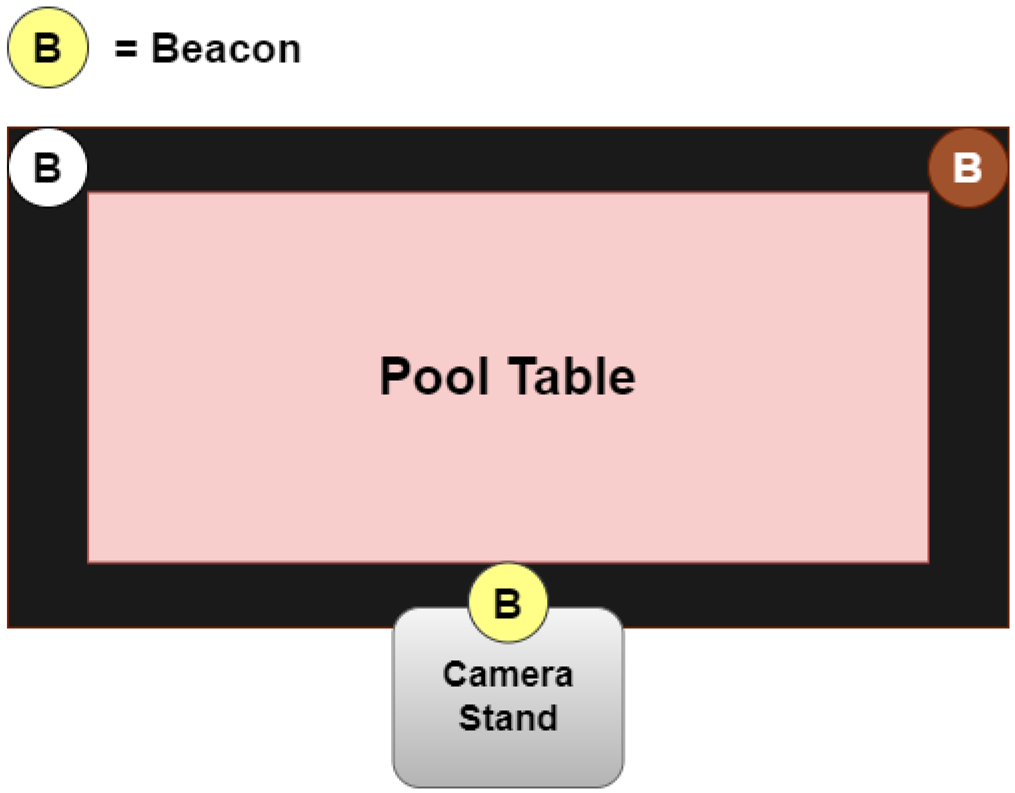


Figure 9.5: User Localization Beacon Layout

10. ADMINISTRATIVE CONTENT

10.1 Project Budget

VISION is a large project that requires a significant amount of hardware and software components. As shown in the table below, the project requires a billiards table, Jetson Nano, camera, multiple BLE beacons, and other costly hardware. To account for the large amount of technology needed, the team had initially set a budget of $800 ($200 per team member). The budget is an upper bound of what the team believes is needed for someone to recreate this project. The team ended up exceeding the budget because a second version of the UWB beacons were purchased (the first set was lost in a fire) and a second version of the PCB was needed due to design issues with the first version.

10.1.1 Bill of Materials

Table 10.1 lists the materials, quantity, and associated cost for the materials needed to implement VISION.

Component	Quantity	Unit Cost	Total
Pool Table	1/2	$450	$225
Anker Powerconf c200 and Stand	1	$100	$100
ESP Microcontrollers	2	$15	$30
Bluetooth Beacons	2 (3-packs)	$100	$200
ESP32 Processors	5	$5	$25
PCB Orders	2	$60	$120
Jetson Nano 4GB Development Kit	1	$200	$200
Speakers	12	$2	$24
Various PCB Components	2	$20	$40
Power cords, keyboards, etc.	1	$50	$50
Tape	1	$20	$20
Total			$1034

Table 10.1: Bill of Materials

10.1.2 Project Financing

The table above is a comprehensive list of the most critical components for VISION. The pool table will be shared with the SCRATCH (group #17) project, meaning the team is only responsible for half of the cost of the pool table. Although the price of the project is above the $800 project budget, there are opportunities to reduce the overall cost. Due to supply chain shortages, most high-power processors (Jetson Nano, Google Coral Dev Board, Raspberry Pi) are not in stock and are subject to third-party resale prices. For individuals wanting to recreate VISION, the Jetson Nano can be swapped out for any modern computer than can run Python. The VISION team is willing to donate the PCB and related supplied to anybody wanting to recreate VISION as well.

10.2 Milestones

VISION is a complex project requiring many different systems to integrate together for a user to play a game of billiards. For this reason, the members of VISION used the summer prior to taking Senior Design 1 to complete the project brainstorming. The goal was for the team to start the documentation process as soon as classes resumed so there would be sufficient time to research the design. There are no projects for VISION to be based upon, so the group wanted to ensure adequate time to resolve any issues arising while conducting research.

The timelines discussed below account for any research compilations that were discovered. The milestones of VISION were mostly completed before the anticipated end dates so that the deliverables were able to be submitted at least a day before the due date. Although the focus of Senior Design 1 was the research and documentation of the project, the team started preliminary testing to show that the ideas being researched are feasible. Proof of concept testing was conducted by each member in their respective area of focus alongside their project research. System integration was performed as soon as the team moved into Senior Design 2. For a more detailed schedule of VISION's goals, view tables 10.2, 10.3 and 10.4.

Task	Start Date	End Date	Duration
Project Brainstorming	Summer	Summer	0 weeks
Project Scope Finalized (Finalize big picture design and what the end goal is)	08/22/2022	08/26/2022	1 week
Individual Research Begins (Begin breaking the project into smaller subsections such as CV or AI)	08/22/2022	09/02/2022	2 weeks
Initial Design Document (Based upon the D&C documents)	08/22/2022	09/05/2022	1.5 weeks
30-Page Milestone (General system design, project motivation, project goals, project concepts)	08/22/2022	09/09/2022	3 weeks
60-Page Milestone (Independent technology research, system requirements, part ideas/availability)	09/10/2022	09/30/2022	3 weeks
90-Page Milestone (Independent technology research, system communication)	10/01/2022	10/21/2022	3 weeks
120-Page Milestone (System testing, PCB design, PCB testing, citations)	10/22/2022	11/11/2022	3 weeks
Group Review: Final Draft	11/14/2022	11/18/2022	1 week

Table 9.2: Senior Design 1 Project Documentation Milestones

Task	Start Date	End Date	Duration
Individual System Design (Create some proof of concept design in hardware or software)	09/05/2022	10/02/2022	4 weeks
Individual System Testing (Develop and demonstrate the proof of concept design to the team)	10/03/2022	10/30/2022	4 weeks
Breadboard Prototyping (Finalize what the PCB will do and breadboard the design)	10/31/2022	11/21/2022	3 weeks
PCB Design / Ordering (Design the PCB in Eagle and order from a reputable PCB company)	11/22/2022	12/12/2022	3 weeks

Table 10.3: Senior Design 1 Project Design Milestones

Task	Start Date	End Date	Duration
PCB Testing (Test all of the PCBs to ensure they work properly)	01/09/2023	01/29/2023	3 weeks
System Integration / Testing (Begin integrating the individual systems together in the main code)	01/30/2023	02/20/2023	4 weeks
Practice Project Demo (Go through a mock project demonstration to ensure everything is functioning)	02/21/2023	03/06/2023	2 weeks
Finalize Documentation (Final edits and construction of the documentation)	03/07/2023	03/20/2023	2 weeks
Practice Final Presentation	03/21/2023	03/31/2023	2 week
Final Presentation Prep	04/01/2023	04/17/2023	2 Weeks

Table 10.4 Senior Design 2 Project Design Milestones

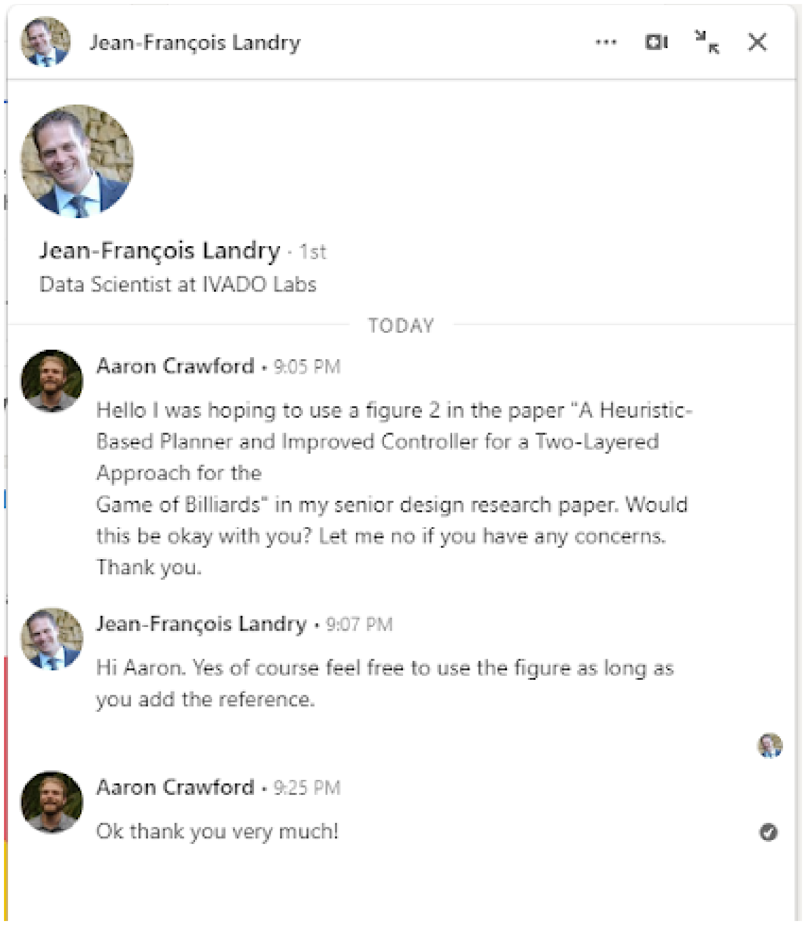
11. PROJECT SUMMARY and CONCLUSION

VISION progressed well throughout the Senior Design 1 semester. The VISION team reviewed many different types of applicable technology and developed a better understanding of what technologies were applicable during project design in Senior Design 2. Furthermore, the team developed a hardware and software design plan that provided positive results in preliminary testing.

One of the largest issues that VISION, and other projects, overcame is the remaining problems in the supply chain. Many parts that VISION would have liked to use were either unavailable or significantly more costly due to having to pay third-party prices. In addition to product unavailability, shipping times, especially from international sources, was still slower than pre-pandemic times. VISION overcame these difficulties by acquiring parts early so that there was no delay to building the design in the spring semester.

The VISION team's dedication to technology exploration in Senior Design 1 allowed the team to discover, discuss, and solve many design issues related to the project's implementation. With a wealth of new knowledge on the subject and many of the necessary components acquired, the VISION team successfully implemented the project in Senior Design 2.

Appendix A: Copyright Permissions


Jean-François Landry

Jean-François Landry · 1st
Data Scientist at IVADO Labs

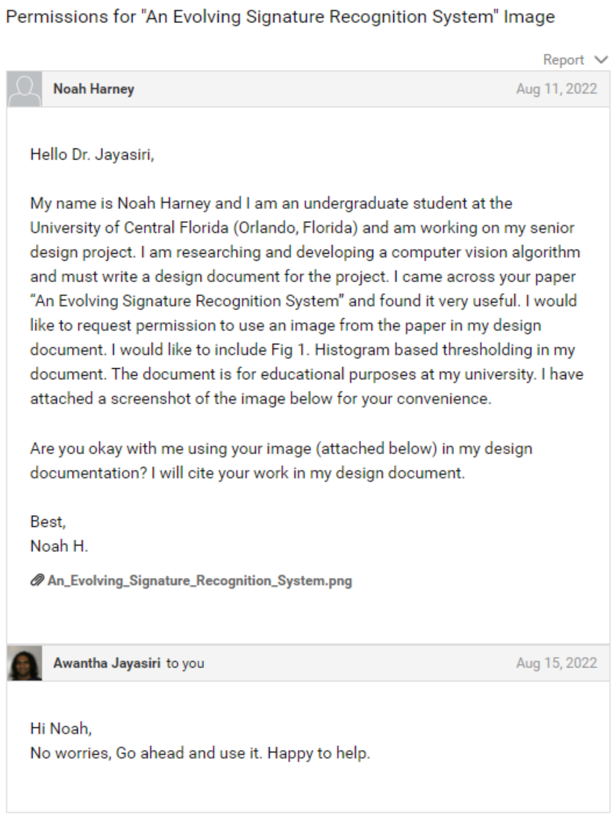
TODAY

Aaron Crawford · 9:05 PM
Hello I was hoping to use a figure 2 in the paper "A Heuristic-Based Planner and Improved Controller for a Two-Layered Approach for the
Game of Billiards" in my senior design research paper. Would this be okay with you? Let me no if you have any concerns. Thank you.

Jean-François Landry · 9:07 PM
Hi Aaron. Yes of course feel free to use the figure as long as you add the reference.

Aaron Crawford · 9:25 PM
Ok thank you very much!

Request for Shot Planner Diagram (Figure 3.1)



Permissions for "An Evolving Signature Recognition System" Image

Report

Noah Harney Aug 11, 2022

Hello Dr. Jayasiri,

My name is Noah Harney and I am an undergraduate student at the University of Central Florida (Orlando, Florida) and am working on my senior design project. I am researching and developing a computer vision algorithm and must write a design document for the project. I came across your paper "An Evolving Signature Recognition System" and found it very useful. I would like to request permission to use an image from the paper in my design document. I would like to include Fig 1. Histogram based thresholding in my document. The document is for educational purposes at my university. I have attached a screenshot of the image below for your convenience.

Are you okay with me using your image (attached below) in my design documentation? I will cite your work in my design document.

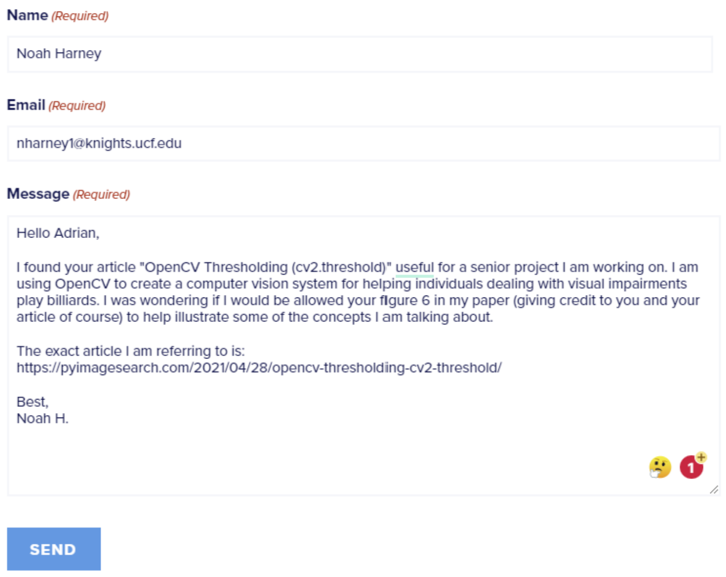
Best,
Noah H.

An_Evolving_Signature_Recognition_System.png

Awantha Jayasiri to you Aug 15, 2022

Hi Noah,
No worries, Go ahead and use it. Happy to help.

Request and Permission for Image of Thresholding Distribution (Figure 3.4)



Name *(Required)*

Noah Harney

Email *(Required)*

nharney1@knights.ucf.edu

Message *(Required)*

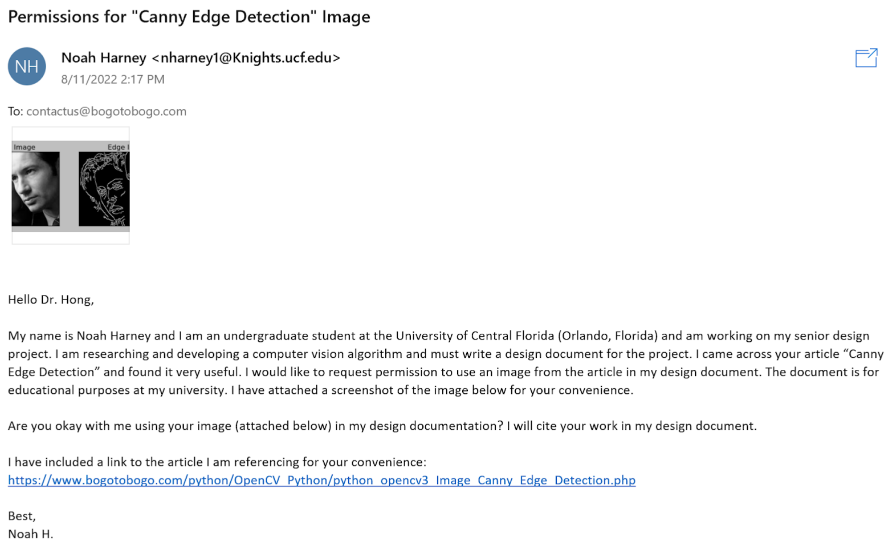
Hello Adrian,

I found your article "OpenCV Thresholding (cv2.threshold)" useful for a senior project I am working on. I am using OpenCV to create a computer vision system for helping individuals dealing with visual impairments play billiards. I was wondering if I would be allowed your figure 6 in my paper (giving credit to you and your article of course) to help illustrate some of the concepts I am talking about.

The exact article I am referring to is:
https://pyimagesearch.com/2021/04/28/opencv-thresholding-cv2-threshold/

Best,
Noah H.

Request for Image of Thresholding (Figure 3.5)



Permissions for "Canny Edge Detection" Image

Noah Harney <nharney1@Knights.ucf.edu>
8/11/2022 2:17 PM

To: contactus@bogotobogo.com

Hello Dr. Hong,

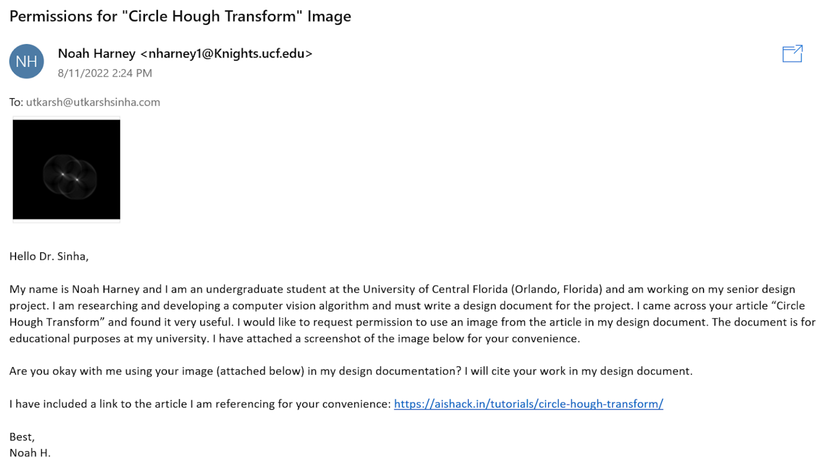
My name is Noah Harney and I am an undergraduate student at the University of Central Florida (Orlando, Florida) and am working on my senior design project. I am researching and developing a computer vision algorithm and must write a design document for the project. I came across your article "Canny Edge Detection" and found it very useful. I would like to request permission to use an image from the article in my design document. The document is for educational purposes at my university. I have attached a screenshot of the image below for your convenience.

Are you okay with me using your image (attached below) in my design documentation? I will cite your work in my design document.

I have included a link to the article I am referencing for your convenience:
https://www.bogotobogo.com/python/OpenCV_Python/python_opencv3_Image_Canny_Edge_Detection.php

Best,
Noah H.

Request for Canny Edge Detection Image (Figure 3.6)



Permissions for "Circle Hough Transform" Image

Noah Harney <nharney1@Knights.ucf.edu>
8/11/2022 2:24 PM

To: utkarsh@utkarshsinha.com

Hello Dr. Sinha,

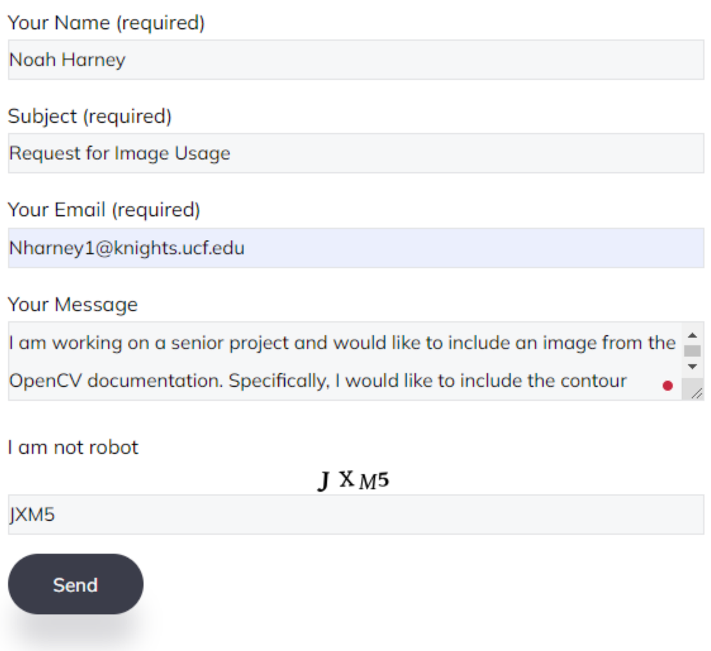
My name is Noah Harney and I am an undergraduate student at the University of Central Florida (Orlando, Florida) and am working on my senior design project. I am researching and developing a computer vision algorithm and must write a design document for the project. I came across your article "Circle Hough Transform" and found it very useful. I would like to request permission to use an image from the article in my design document. The document is for educational purposes at my university. I have attached a screenshot of the image below for your convenience.

Are you okay with me using your image (attached below) in my design documentation? I will cite your work in my design document.

I have included a link to the article I am referencing for your convenience: https://aishack.in/tutorials/circle-hough-transform/

Best,
Noah H.

Request for Hough Circle Transform Image (Figure 3.7)



Your Name (required)

Noah Harney

Subject (required)

Request for Image Usage

Your Email (required)

Nharney1@knights.ucf.edu

Your Message

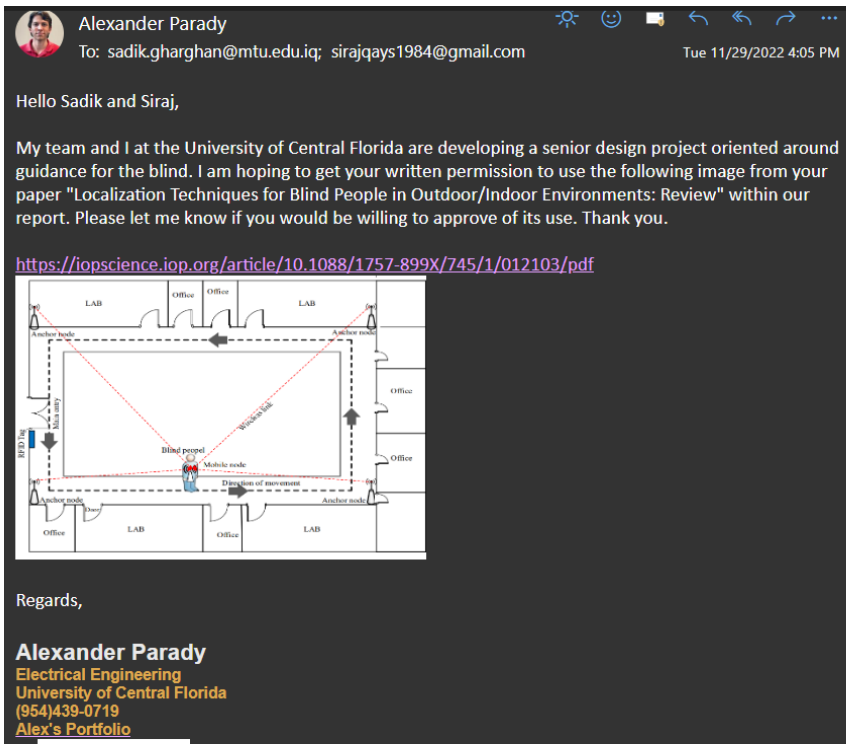
I am working on a senior project and would like to include an image from the OpenCV documentation. Specifically, I would like to include the contour

I am not robot

JXM5

JXM5

Request for Douglas-Peucker Algorithm (Figure 3.8)



Alexander Parady
To: sadik.gharghan@mtu.edu.iq; sirajqays1984@gmail.com
Tue 11/29/2022 4:05 PM

Hello Sadik and Siraj,

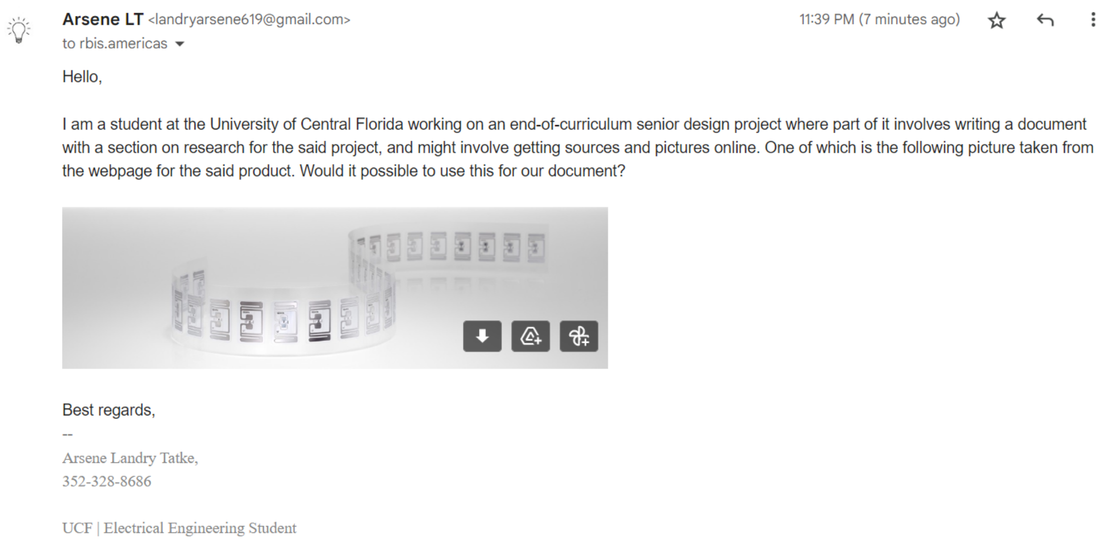
My team and I at the University of Central Florida are developing a senior design project oriented around guidance for the blind. I am hoping to get your written permission to use the following image from your paper "Localization Techniques for Blind People in Outdoor/Indoor Environments: Review" within our report. Please let me know if you would be willing to approve of its use. Thank you.

https://iopscience.iop.org/article/10.1088/1757-899X/745/1/012103/pdf

Regards,

Alexander Parady
Electrical Engineering
University of Central Florida
(954)439-0719
Alex's Portfolio

Request for Previous System Indoor Localization Design (Figure 3.9)



Arsene LT <landryarsene619@gmail.com>
to rbis.americas

11:39 PM (7 minutes ago)

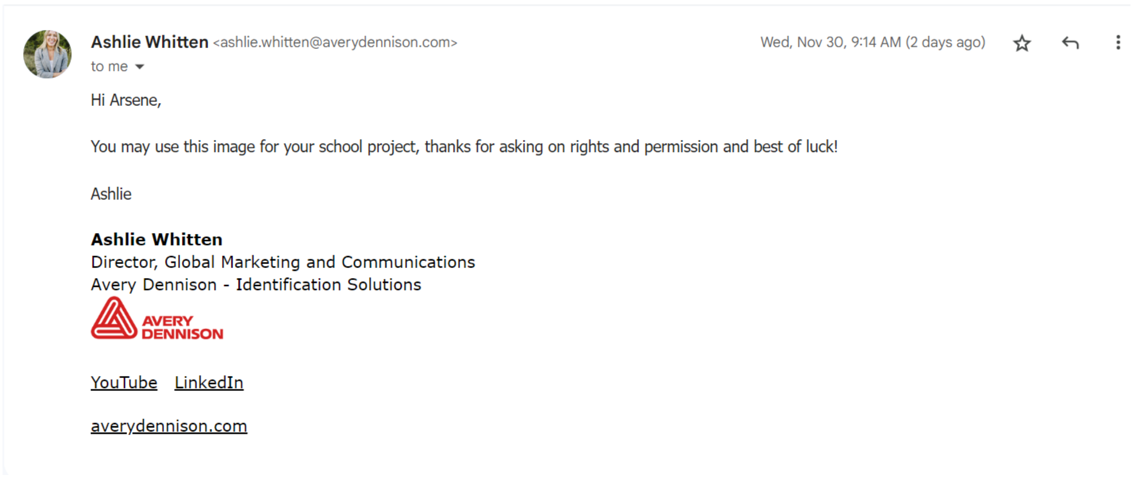
Hello,

I am a student at the University of Central Florida working on an end-of-curriculum senior design project where part of it involves writing a document with a section on research for the said project, and might involve getting sources and pictures online. One of which is the following picture taken from the webpage for the said product. Would it possible to use this for our document?

Best regards,
--
Arsene Landry Tatke,
352-328-8686

UCF | Electrical Engineering Student

Request for Image of Avery Dennison's AD-172u7 Inlays (Figure 3.10)



Ashlie Whitten <ashlie.whitten@averydennison.com>
to me

Wed, Nov 30, 9:14 AM (2 days ago)

Hi Arsene,

You may use this image for your school project, thanks for asking on rights and permission and best of luck!

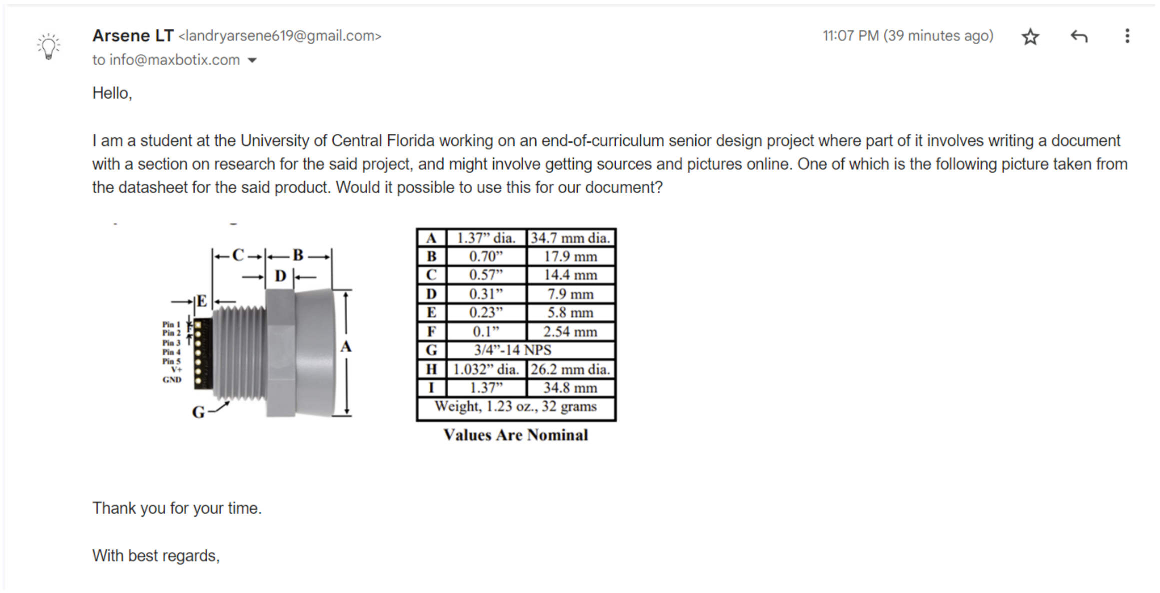
Ashlie

Ashlie Whitten
Director, Global Marketing and Communications
Avery Dennison - Identification Solutions

YouTube LinkedIn

averydennison.com

Approval for Image of Avery Dennison's AD-172u7 Inlays (Figure 3.10)

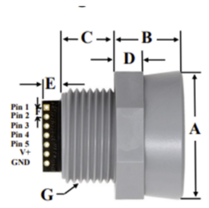


Arsene LT <landryarsene619@gmail.com>
to info@maxbotix.com

11:07 PM (39 minutes ago)

Hello,

I am a student at the University of Central Florida working on an end-of-curriculum senior design project where part of it involves writing a document with a section on research for the said project, and might involve getting sources and pictures online. One of which is the following picture taken from the datasheet for the said product. Would it possible to use this for our document?



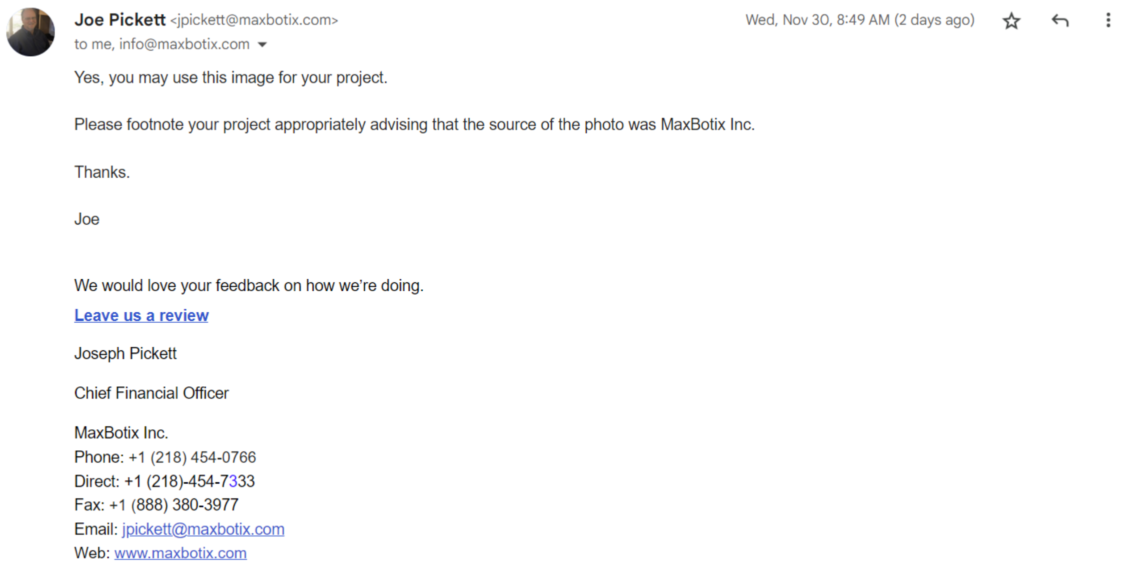
A	1.37" dia.	34.7 mm dia.
B	0.70"	17.9 mm
C	0.57"	14.4 mm
D	0.31"	7.9 mm
E	0.23"	5.8 mm
F	0.1"	2.54 mm
G	3/4"-14 NPS	
H	1.032" dia.	26.2 mm dia.
I	1.37"	34.8 mm
Weight, 1.23 oz., 32 grams		

Values Are Nominal

Thank you for your time.

With best regards,

Request for image of Model and Dimensions of Compact Housing HRXL-MaxSonar Model (Figure 3.13)



Joe Pickett <jpickett@maxbotix.com>
to me, info@maxbotix.com

Wed, Nov 30, 8:49 AM (2 days ago)

Yes, you may use this image for your project.

Please footnote your project appropriately advising that the source of the photo was MaxBotix Inc.

Thanks.

Joe

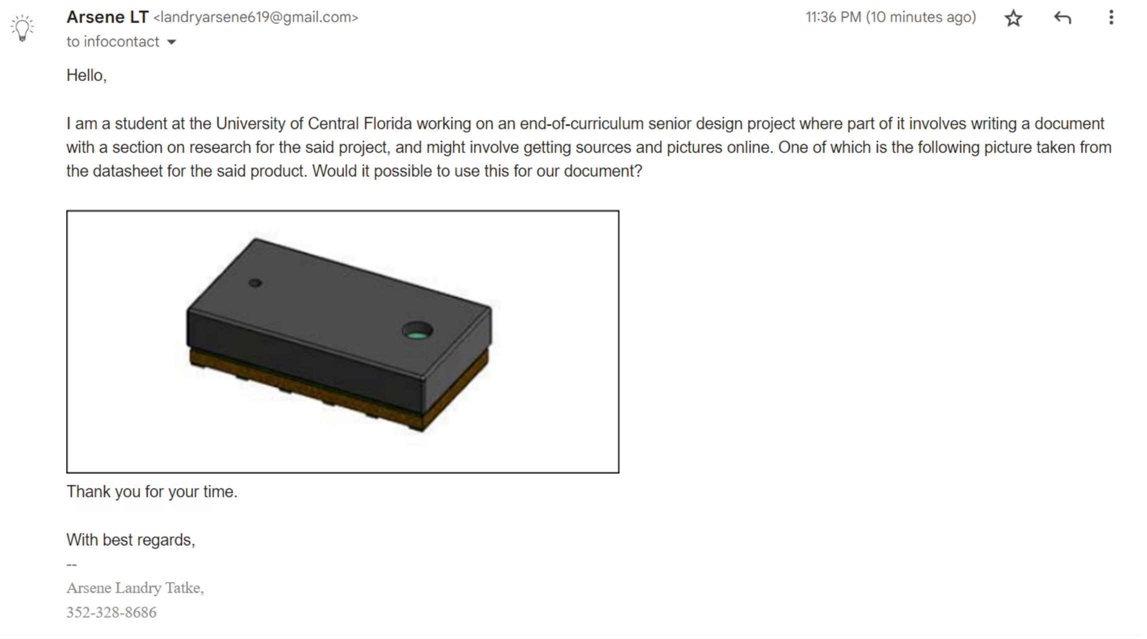
We would love your feedback on how we're doing.
Leave us a review

Joseph Pickett

Chief Financial Officer

MaxBotix Inc.
Phone: +1 (218) 454-0766
Direct: +1 (218)-454-7333
Fax: +1 (888) 380-3977
Email: jpickett@maxbotix.com
Web: www.maxbotix.com

Approval for image of Model and Dimensions of Compact Housing HRXL-MaxSonar Model (Figure 3.13)



Arsene LT <landryarsene619@gmail.com>
to infocontact

11:36 PM (10 minutes ago)

Hello,

I am a student at the University of Central Florida working on an end-of-curriculum senior design project where part of it involves writing a document with a section on research for the said project, and might involve getting sources and pictures online. One of which is the following picture taken from the datasheet for the said product. Would it possible to use this for our document?

Thank you for your time.

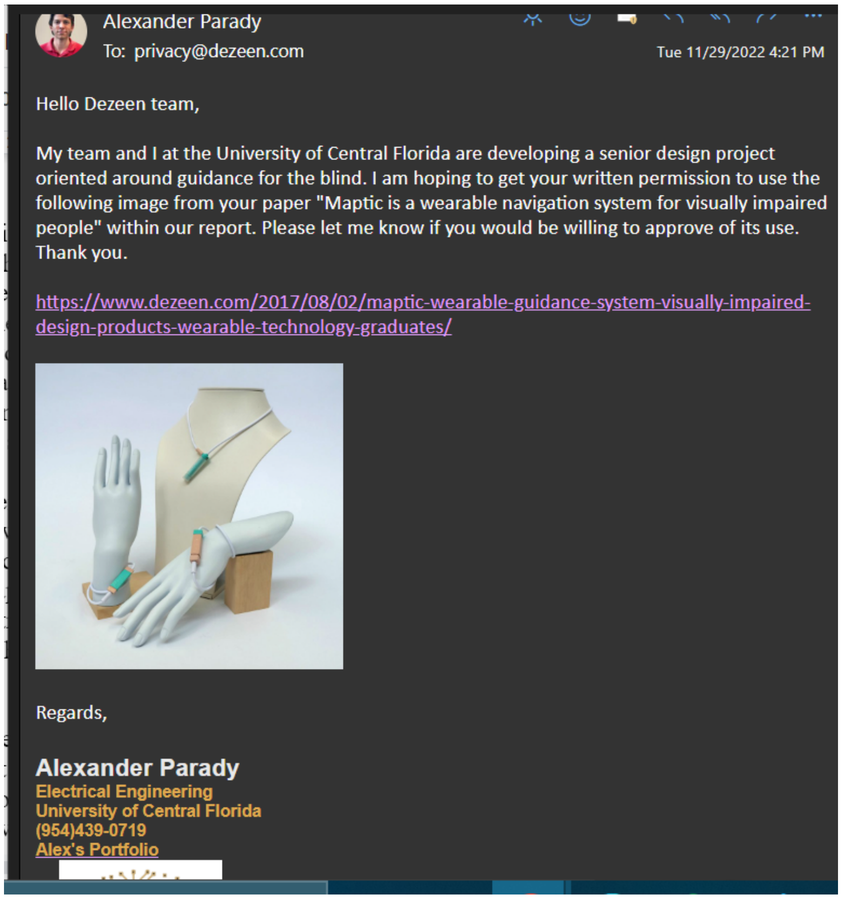
With best regards,

--

Arsene Landry Tatke,

352-328-8686

Request for image of VL53L0X Time-of-Flight Ranging and Gesture Detection Sensor (Figure 3.14)



Alexander Parady
To: privacy@dezeen.com
Tue 11/29/2022 4:21 PM

Hello Dezeen team,

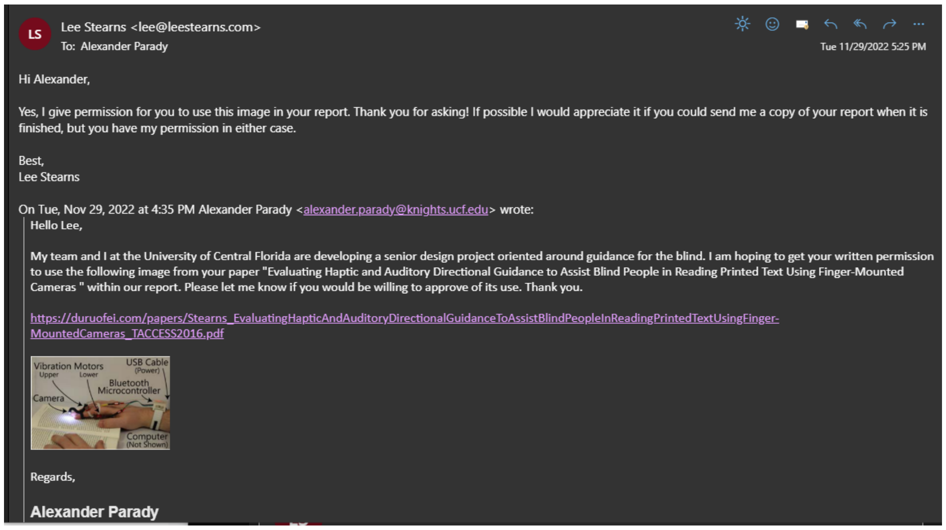
My team and I at the University of Central Florida are developing a senior design project oriented around guidance for the blind. I am hoping to get your written permission to use the following image from your paper "Maptic is a wearable navigation system for visually impaired people" within our report. Please let me know if you would be willing to approve of its use. Thank you.

https://www.dezeen.com/2017/08/02/maptic-wearable-guidance-system-visually-impaired-design-products-wearable-technology-graduates/

Regards,

Alexander Parady
Electrical Engineering
University of Central Florida
(954)439-0719
Alex's Portfolio

Request for Maptic Haptic Feedback Apparatus (Figure 3.17)



Lee Stearns <lee@leestearns.com>
To: Alexander Parady
Tue 11/29/2022 5:25 PM

Hi Alexander,

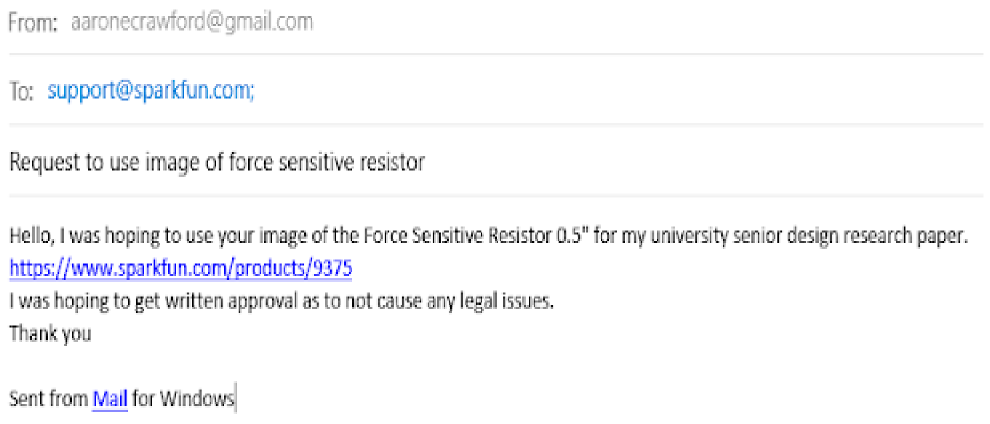
Yes, I give permission for you to use this image in your report. Thank you for asking! If possible I would appreciate it if you could send me a copy of your report when it is finished, but you have my permission in either case.

Best,
Lee Stearns

On Tue, Nov 29, 2022 at 4:35 PM Alexander Parady <alexander.parady@knights.ucf.edu> wrote:

> Hello Lee,
>
> My team and I at the University of Central Florida are developing a senior design project oriented around guidance for the blind. I am hoping to get your written permission to use the following image from your paper "Evaluating Haptic and Auditory Directional Guidance to Assist Blind People in Reading Printed Text Using Finger-Mounted Cameras " within our report. Please let me know if you would be willing to approve of its use. Thank you.
>
> https://duruofei.com/papers/Stearns_EvaluatingHapticAndAuditoryDirectionalGuidanceToAssistBlindPeopleInReadingPrintedTextUsingFinger-MountedCameras_TACCESS2016.pdf
>
> Regards,
>
> **Alexander Parady**

Request for HandSight Haptic Feedback Apparatus (Figure 3.18)



From: aaronecrawford@gmail.com

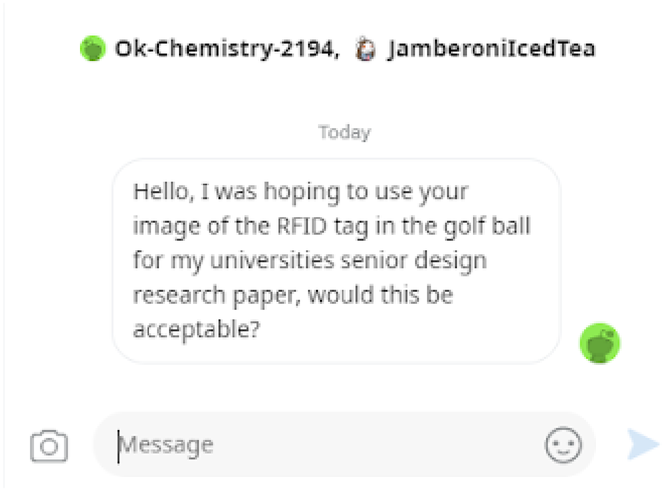
To: support@sparkfun.com;

Request to use image of force sensitive resistor

Hello, I was hoping to use your image of the Force Sensitive Resistor 0.5" for my university senior design research paper.
https://www.sparkfun.com/products/9375
I was hoping to get written approval as to not cause any legal issues.
Thank you

Sent from Mail for Windows

Approval for Image of Force Sensitive Resistor from Sparkfun (Figure 3.20)

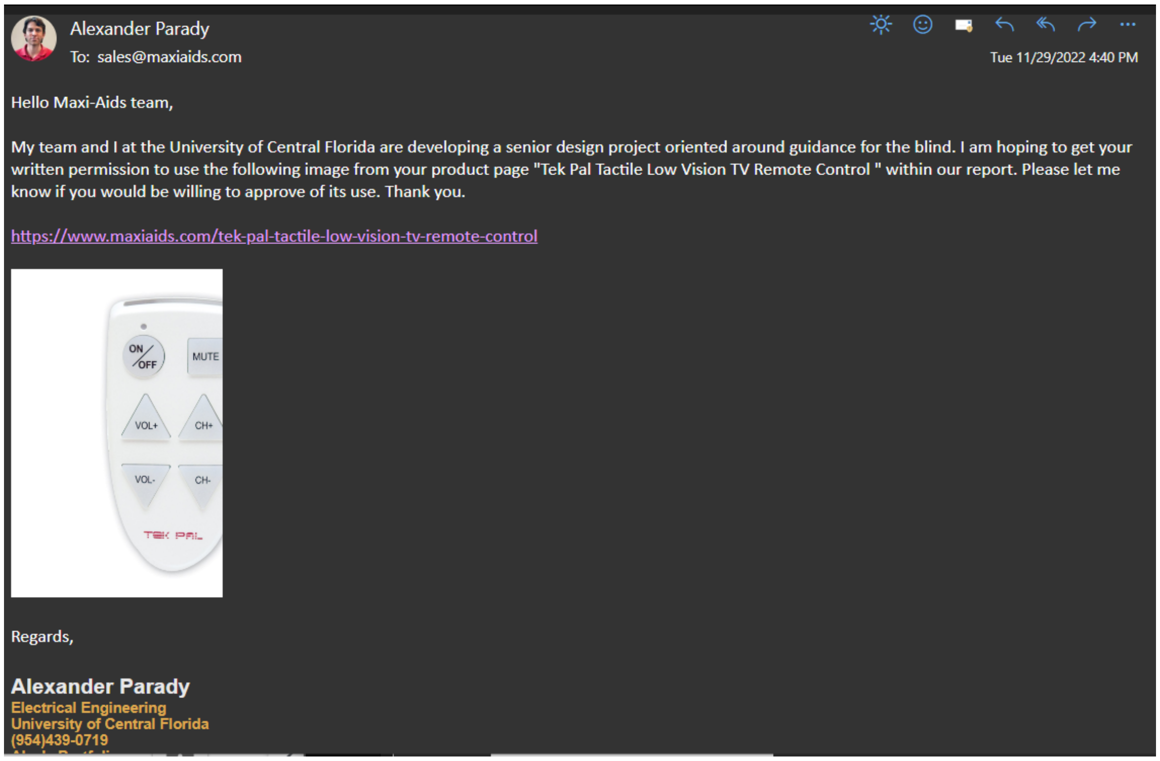


Ok-Chemistry-2194, JamberoniIcedTea

Today

Hello, I was hoping to use your image of the RFID tag in the golf ball for my universities senior design research paper, would this be acceptable?

Request to Use Image of RFID Tag in Golf Ball from Reddit User (Fig 3.21)



Alexander Parady
To: sales@maxiaids.com
Tue 11/29/2022 4:40 PM

Hello Maxi-Aids team,

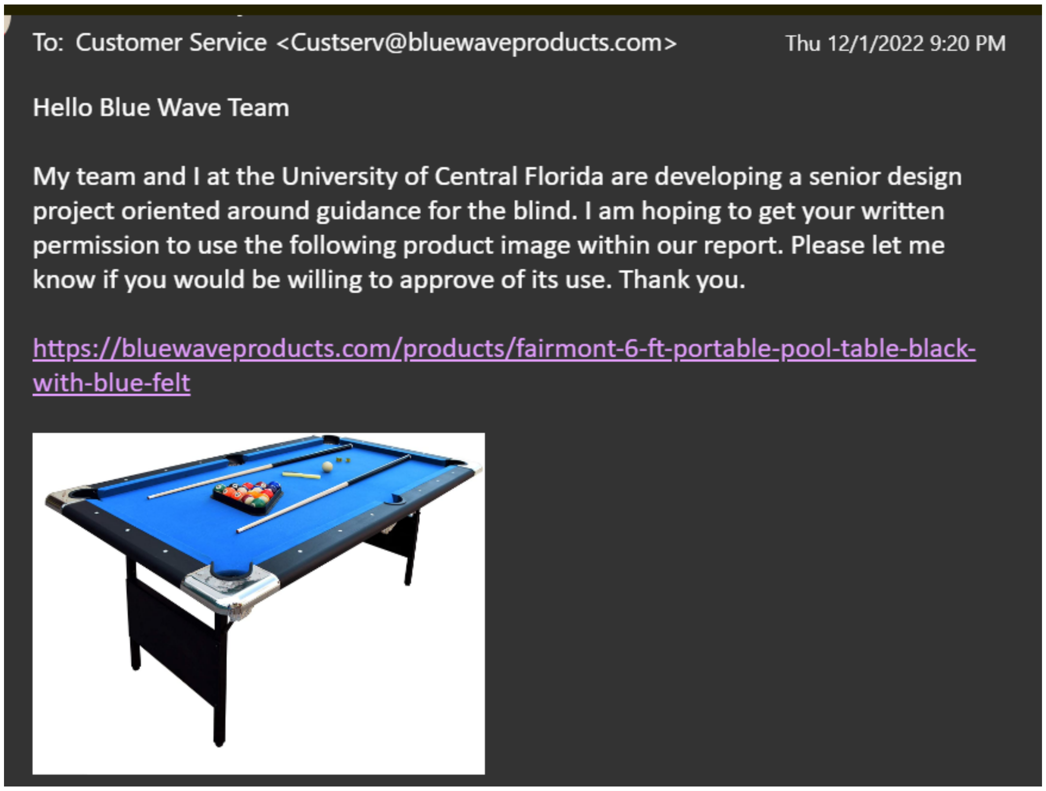
My team and I at the University of Central Florida are developing a senior design project oriented around guidance for the blind. I am hoping to get your written permission to use the following image from your product page "Tek Pal Tactile Low Vision TV Remote Control " within our report. Please let me know if you would be willing to approve of its use. Thank you.

https://www.maxiaids.com/tek-pal-tactile-low-vision-tv-remote-control

Regards,

Alexander Parady
Electrical Engineering
University of Central Florida
(954)439-0719

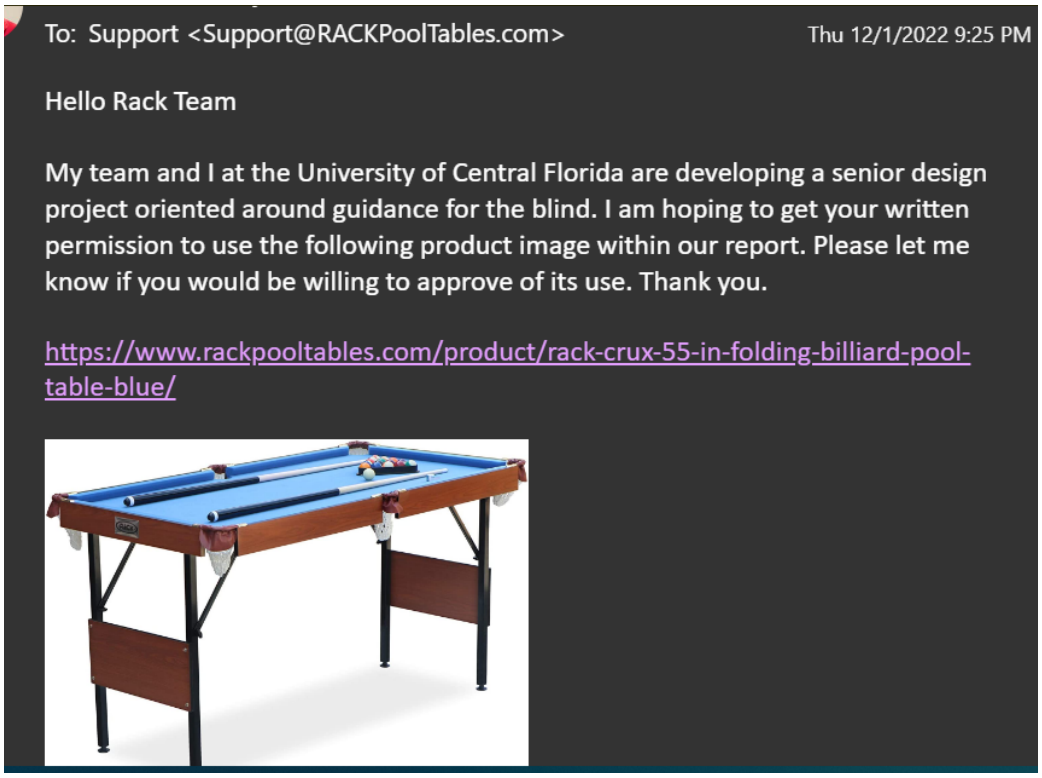
Request for TV Remote for the Visually Impaired (Figure 3.23)


To: Customer Service <Custserv@bluewaveproducts.com> Thu 12/1/2022 9:20 PM

Hello Blue Wave Team

My team and I at the University of Central Florida are developing a senior design project oriented around guidance for the blind. I am hoping to get your written permission to use the following product image within our report. Please let me know if you would be willing to approve of its use. Thank you.

https://bluewaveproducts.com/products/fairmont-6-ft-portable-pool-table-black-with-blue-felt


To: Support <Support@RACKPoolTables.com> Thu 12/1/2022 9:25 PM

Hello Rack Team

My team and I at the University of Central Florida are developing a senior design project oriented around guidance for the blind. I am hoping to get your written permission to use the following product image within our report. Please let me know if you would be willing to approve of its use. Thank you.

https://www.rackpooltables.com/product/rack-crux-55-in-folding-billiard-pool-table-blue/

Request for Blue Wave's Fairmount Table (Top) & Rack's Crux 55 Table (Bottom) (Figure 5.1)

Appendix C: References

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Davide Cannizzaro Politecnico di Torino. “A Comparison Analysis of BLE-Based Algorithms for Localization in Industrial Environments.” 26 February 2022, https://www.researchgate.net/publication/345670871_Indoor_Navigation_System_using_BLE_and_ESP32. Accessed 30 November 2022.

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